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Comparison of Ozone Contactors for Municipal Wastewater Effluent Disinfection

Packed Column Versus Jet Scrubber

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16. ABSTRACT Pilot scale investigations were made comparing two ozone contactors, a jet scrubber and a packed column, for ozone utilization and effluent coliform reduction efficiency. The contactors were operated in three phases: (1) Batch operational phase contactors were operated separately under identical conditions on a batch sample of activated sludge effluent. (2) Parallel operational phase; both contactors were operated in parallel on the same activated sludge effluent. (3) Continuous operational phase; both contactors were operated on the same activated sludge effluent to achieve a specified coliform reduction.

Results showed that the packed column significantly outperformed the jet scrubber with respect to microorganisms reduction. Effluent quality interfered with disinfection in both contactors, the most important variables being chemical oxygen demand (total and soluble) and organic carbon. Initial bacterial density and ozoen residual were also important factors affecting log reduction of coliforms and fecal streptococci in both contactors.

The packed column significantly outperformed the jet scrubber with respect to ozone utilization. Organic demand measured as TCOD, SCOD, and TOC significantly affected ozone utilization at high but not low ozone dosages.

These results indicate that the use of a single stage jet scrubber type ozone contactor is not suitable for wastewater disinfection with ozone.

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COMPARISON OF OZONE CONTACTORS FOR MUNICIPAL WASTEWATER EFFLUENT DISINFECTION

Packed Column Versus Jet Scrubber

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

As part of these activities, this report was prepared for use by design engineers whose responsibility is to design the most efficient, cost-effective ozone contacting system for achieving a specified bacteriological quality of wastewater effluent.

Francis T. Mayo
Director
Municipal Environmental
Research Laboratory

PREFACE

In January 1974, a U. S. Environmental Protection Agency (USEPA) Task Force was formed to review USEPA policy on wastewater disinfection and the use of chlorine. The Task Force recognized that chlorine and chlorine-based compounds were being used almost exclusively for the disinfection of wastewater. While chlorine was considered an effective disinfectant with respect to meeting bacteriological standards and was adequately protecting public health, there were potential dangers associated with the use of chlorine. Disinfection of wastewater with chlorine could result in the formation of halogenated organic compounds which have been identified as potential carcinogens. Considerable data also existed that chlorination of wastewater could result in residual chlorine or chloramine levels that could be toxic to aquatic life. The Task Force concluded that, in view of the fact that existing regulations inadvertently encouraged the use of chlorine, a national regulation requiring disinfection would further compound the potential problems associated with the chlorination of wastewater.

The Agency recognized that protection of public health from disease continues to be the primary objective under the present system of regulation of disinfection of municipal wastewater by means of State standards. It also recognized that continuous disinfection in some localities was not necessary to insure public health protection. The exclusive use of chlorine for disinfection should not be continued where protection of aquatic life is of primary consideration. Alternate means of disinfection or disinfectant control (i.e., dechlorination) must be considered where public health hazards and potential adverse impact on the aquatic or human environments exist.

Consequently, on July 26, 1976, USEPA amended the Secondary Treatment Information regulation contained in 40 CFR Part 133, Section 304(d)(1) of the Federal Water Pollution Control Act Amendments of 1972. The amendment deleted the fecal coliform bacteria limitation from the definition of secondary treatment. Reliance on water quality standards for establishment of disinfection requirements for publicly owned treatment works was selected by the Agency to replace the limitations in 40 CFR Part 133.

The USEPA Municipal Wastewater Disinfection Program is intensively pursuing development of alternative disinfection technology which could reliably achieve any specified bacteriological limitation without adversely affecting the environment. Ozonation appears to be the most promising alternative process presently under investigation. However, ozone is both cost and energy sensitive. Generation of ozone by corona discharge is only about 10 percent efficient from a power consumption standpoint. Thus, it becomes imperative that all or most of the ozone produced on-site must be utilized in the most efficient manner to prevent needless loss of energy and resources.

An in-house research program was initiated at USEPA-Cincinnati's experimental pilot plant located in the Robert A. Taft Laboratory building. The purpose of the project is to compare and evaluate various types of gas-liquid contacting devices in parallel on the same wastewater effluent so that the conditions necessary for microorgansim reduction efficiency and mass transfer efficiency can be properly defined and quantified. The ultimate goal is to optimize ozone contacting to achieve the desired bacteriological quality and reduce operational costs of ozonation by eliminating excessive loss.

This report is the first of a series on the comparative performance of ozone contactors. It discusses the results of a study comparing a packed column with a jet scrubber operating in parallel on conventional activated sludge effluent.

ABSTRACT

This research effort was initiated with the overall objective of determining which engineering and microbial operating parameters must be controlled with respect to municipal effluent disinfection and ozone utilization for various generic contactors.

Pilot scale investigations were made comparing two ozone contactors, a jet scrubber and a packed column, for ozone utilization and coliform reduction efficiency. These investigations were conducted in three phases: (1) batch operation phase - both contactors were operated separately under identical conditions using a batch sample of activated sludge effluent; (2) parallel operational phase - both contactors were operated in parallel on the same activated sludge effluent; and (3) continuous operational phase - both contactors were operated in parallel to achieve a three log reduction of coliform bacteria on the same activated sludge effluent. The effluent was characterizied by determining COD, TOC, SS, NH_4-N, NO_3-N, NO_2-N, pH and turbidity.

Bacterial enumerations included total and fecal coliforms, fecal streptococci, and Salmonella spp. Ozone gas concentrations, before and after contacting, were determined iodometrically, and ozone residual was determined by amperometric techniques.

Results showed that the packed column significantly outperformed the jet scrubber with respect to microorganism reduction and efficiency of ozone utilization. Wastewater effluent quality interfered with disinfection in both contactors, the most important variables being chemical oxygen demand (total and soluble) and organic carbon. Initial bacterial density and ozone residual were also important factors affecting log reduction of coliforms and fecal streptococci in both contactors.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

ANOVA	-- analysis of variance
COD	-- chemical oxygen demand
df	-- degree of freedom
F	-- F-statistic
FC	-- fecal coliform
FCLR	-- fecal coliform log reduction
FS	-- fecal streptococci
FSLR	-- fecal streptococci log reduction
kg	-- kilogram
kg/d	-- kilogram per day
kg/h	-- kilogram per hour
kPa	-- kilopascals pressure
kW	-- kilowatt
kWh/kg	-- kilowatt hour per kilogram
ℓ/min	-- litre per minute
m^3/d	-- cubic meter per day
MCWTP	-- Muddy Creek Wastewater Treatment Plant
mg/ℓ	-- milligram per litre
mg/min	-- milligram per minute
mm Hg	-- millimeter mercury
MS	-- mean square
n	-- number of observations
r	-- correlation coefficient
r^2	-- coefficient of determination
SCOD	-- soluble chemical oxygen demand
S.D.	-- standard deviation
t	-- "t"-statistic
TC	-- total coliform
TCLR	-- total coliform log reduction
TKN	-- total Kjeldahl nitrogen
TOC	-- total organic carbon
TSS	-- total suspended solids
VSS	-- volatile suspended solids

SYMBOLS

α	-- probability of error
C_k	-- contactor designation (i.e., packed column or jet scrubber)
C_o	-- ozone consumption (U_o - R_o)

^{o}C	-- degree centigrade
D_j	-- dosage level
D_o	-- applied ozone dosage
ΔY_{lm}	-- log mean concentration difference of ozone in the gas phase in equilibrium with ozone in the liquid phase
Fe	-- iron
G	-- gas flow rate
G/L	-- ratio of gas flow rate to liquid flow rate
H	-- Henry's Constant
HCl	-- hydrochloric acid
H_2SO_4	-- sulfuric acid
KgV	-- mass transfer coefficient
KgVa	-- overall mass transfer coefficient
KI	-- potassium iodide
L	-- liquid flow rate
Mn	-- manganese
N	-- ozone transferred from the gas phase into the liquid
$Na_2S_2O_3$	-- sodium thiosulfate
NH_4^+-N	-- ammonium nitrogen
NO_2^--N	-- nitrite nitrogen
NO_3^--N	-- nitrate nitrogen
ORG-N	-- organic nitrogen
O_3	-- ozone
R_i	-- replicate
R_o	-- ozone residual
s_d	-- standard deviation of the difference
U_o	-- ozone utilization
X	-- total coliform density after ozonation (no./100 mℓ)
X_o	-- initial total coliform density (no./100 mℓ)
$\overline{X}$	-- mean
$\overline{X}_d$	-- difference between means
x	-- ozone concentration in the effluent (mols O_3/mol liq)
Y	-- fecal coliform density after ozonation (no./100 mℓ)
Y_o	-- initial fecal coliform density (no./100 mℓ)
Y_1	-- ozone concentration in the inlet gas (mg/ℓ)
Y_2	-- ozone concentration in the exhaust gas (mg/ℓ)
y^*	-- partial pressure of ozone gas in equilibrium with dissolved ozone
Z	-- fecal streptococci density after ozonation (no./100 mℓ)
Z_o	-- initial fecal streptococci density (no./100 mℓ)

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SECTION 1

INTRODUCTION

Ozonation is rapidly gaining ground in the U.S. as a viable wastewater disinfection process alternative to chlorination. However, the relatively high capital and operating costs of ozone generating equipment, as compared to chlorination, have hampered progress in attainment of widespread acceptability. Any process development which offers promise in reducing the overall costs of ozonation will accelarate that acceptability.

Ozone is a potent oxidizing agent and its reaction with oxidizable materials is non-selective. The demand exerted by organic matter in effluents can have a marked influence on the disinfection efficiency and reliability of ozone. Care must be exercised in making certain that the ozone produced is utilized in the most efficient manner; otherwise, the operating costs of ozonation may be needlessly high due to excessive use of energy resources. Detailed evaluations on gas-liquid contacting devices are needed so that ozone utilization can be optimized, reliability established, and operating costs identified.

Several studies are reported in the literature describing either the disinfection performance or the mass transfer capability of different contacting devices (8,14,15,18,19). Ghan et al. (8) evaluated three commercially available contacting devices: a bubble diffuser, a positive pressure injector, and a multi-stage mixing pump. The authors based their evaluation on ozone utilization, defined as the difference in the ozone concentration between the feed gas and exhaust gas. Ozone utilization was converted to a percent by dividing the difference by the inlet gas concentration and multiplying by 100. Percent ozone utilized in each contactor was plotted as a function of applied ozone dosage. Results indicated 90 percent ozone utilization in the mixing pump up to 50 mg/ℓ applied ozone, while the percent utilization in the other two contactors decreased markedly with increasing dosage. They concluded that the higher utilization in the mixing pump was due to the splitting of the ozone gas stream into four injection points, thus maintaining a low ozone dosage at each addition point. Later studies with a multi-stage, sparged system confirmed that a 90 percent utilization efficiency could be readily achieved.

Masschelein et al. (13,14) examined the ozone utilization efficiency of various contacting devices. Systems studied included: (1) a multi-stage, porous-pipe diffuser system operating in a countercurrent flow configuration; (2) an injection system, similar in principle to a commercially available positive pressure injection system; and (3) different types of single-stage or multi-stage stirred turbine reactors. Comparisons were made on ozone utilization in water and on total energy consumption. No bacteriological data

were gathered, nor were parallel studies performed.

Nebel et al. (18) evaluated the rate of phenol oxidation in various ozone mixing devices. They found that an important consideration in determining the economic feasibility of a given mixer was whether extensive pumping of the liquid to be treated is necessary. Parallel studies were not performed.

In 1974, Rosen et al. (19) postulated a conceptual model for ozone disinfection. Their model assumes that the rate of reaction of ozone with bacteria is virtually instantaneous and that ozone disinfection occurs by direct cell lysis. It was further assumed that lysis would result from direct contact of a microorganism and an ozone gas bubble. Thus, they suggested that disinfection is independent of dissolved ozone concentration and that the rate of disinfection is not limited by the bulk mass transfer rate of ozone into solution. This concept formed the basis for design of the positive pressure injection system.

Recently, Farooq et al. (7) tested this hypothesis by observing the different responses of yeasts and acid-fast bacteria to ozone under different experimental conditions: (1) in the presence of both ozone bubbles and ozone residual; (2) in the presence of ozone residual alone; and (3) in the presence of ozone bubbles alone. They found that the primary microbicidal effect occurred as a result of dissolved ozone. The presence of bubbles enhanced microorganism reduction slightly, but the enhancement was not of such a magnitude to affirm the validity of the bubble hypothesis. Since the primary effect was due to dissolved ozone, disinfection efficiency would not be independent of dissolved ozone concentration.

The project reported herein was initiated to evaluate various types of ozone contacting devices operating in parallel on the same wastewater effluent, so that the disinfection efficiency of ozone can be optimized and operating costs evaluated. The types of contactors to be used in the study were selected as representative of a variety of standard gas-liquid mixing principles in the chemical engineering field and were not necessarily the most efficient for wastewater effluent disinfection. The thrust of the study was not achievement of a specified microbial density in the effluent, but rather comparative log reductions under controlled conditions with definition of the process variables most effectively influencing disinfection. The total wastewater flow available at the experimental pilot facility (described in the next section) is approximately 150 ℓ/min. Thus, only two contactors, each with a design capacity of 75 ℓ/min, can be evaluated at any one given time. A packed column is serving as the base unit, the performance of which will be compared individually with all other contacting units. Other contacting systems to be investigated in the future include: (1) a positive pressure injector, (2) a bubble diffuser, and (3) a stirred turbine reactor. This report concerns the comparison of the packed column with the jet scrubber.

SECTION 2

CONCLUSIONS

Results of this ozone contactor evaluation have indicated that a jet scrubber type contactor is not efficient for effluent disinfection with ozone. The most important factor affecting microorganism reduction in the jet scrubber was ozone residual. As the ozone residual levels increased, the exhaust gas concentrations, by necessity, increased. Maintenance of an ozone residual in the jet scrubber, which operated in a concurrent flow configuration, was predicated upon maintenance of a high concentration of ozone in the gas phase in equilibrium with the liquid phase. Performance of the jet scrubber was further hampered by the exceedingly short residence time (<3 seconds at 75 ℓ/min liquid flow rate). Thus, microorganism reduction in in the jet scrubber was poor.

The packed column, which was operated in a countercurrent mode, exhibited a higher mass transfer driving force. Consequently, more ozone was utilized, higher residuals were achieved, and microorganism reduction was better.

The packed column significantly outperformed the jet scrubber with respect to microorganism reduction and efficiency of ozone utilization. Wastewater effluent quality interfered with disinfection in both contactors, the most important variable being chemical oxygen demand (total and soluble) and organic carbon. Initial bacterial density was also an important factor affecting log reduction of coliforms and fecal streptococci in both contactors.

The packed column was superior to the jet scrubber with respect to percent ozone utilization, regardless of effluent quality and the magnitude of applied dosage. This superiority was significant at all dosage levels employed. With respect to actual ozone utilized, the packed column was superior to the jet scrubber regardless of effluent quality, but the difference between the contactors increased with increasing dosage.

An analysis of variance of the ozone utilization data from a factorial experiment indicated that effluent quality did not significantly affect overall ozone utilization in both contactors. However, linear regression analyses of the data from each contactor at each individual dosage level revealed that organic demand measured by TCOD, SCOD, and TOC significantly affected ozone utilization in both contactors at high but not at low dosage levels. Coliform reduction was adversely affected in both contactors by TCOD, SCOD, and TOC at applied ozone dosage levels <13.1 mg/ℓ and by TKN and organic-N at 19.5 mg/ℓ applied ozone. It was concluded that at low doses (i.e., 4.9 and 9.7 mg/ℓ ozone), ozone utilization was mass transfer limited,

while at higher dosages (i.e. >9.7 mg/ℓ ozone) it was reaction rate limited. Coliform reduction was reaction-rate limited at all dosage levels.

Ozone residual and ozone consumption (i.e., the difference between ozone utilization and residual) were significantly affected by effluent quality in both contactors.

Coliform reductions in the pilot plant effluent to levels less than 100 total coliform/100 mℓ were achieved in the packed column only at an applied dosage of 19.5 mg/ℓ. Fecal coliform levels less than 200/100 mℓ were approached in the packed column at 19.5 mg/ℓ applied ozone, but not in the jet scrubber at any dosage.

SECTION 3

RECOMMENDATIONS

(1) Studies with other contactors should be conducted in a manner similar to that described in this report. It is essential that gas-liquid contacting be optimized to eliminate inefficient utilization of the ozone generated.

(2) Since ozone residuals are so transient and short-lived, more accurate methods of measurement of such residuals should be devised so that disinfection control by residual monitoring can be made possible.

(3) In this study, applied dosage was varied by maintaining a constant ozone gas concentration and varying the gas flow rate. In subsequent studies, dosage should also be varied by changing the ozone gas concentration and maintaining a constant gas flow rate. This will enable a better determination of the optimum operating conditions for a specific contactor.

SECTION 4

MATERIALS AND METHODS

SOURCES OF WASTEWATER EFFLUENT

Muddy Creek Wastewater Treatment Plant Effluent

During the first few months of the project, secondary effluent from the Muddy Creek Wastewater Treatment Plant served as the wastewater source for the ozone disinfection studies. This plant, operated by the Metropolitan Sewer Board of Greater Cincinnati, is a conventional activated sludge system treating approximately 57,000 m^3/day of domestic wastewater.

On the day of an experiment, 20 m^3 of Muddy Creek effluent were drawn into a tank truck and transported to the experimental pilot plant located at the Robert A. Taft Laboratory building. The effluent was pumped from the tank truck through a magnetic flow meter and split into two lines. Both lines were suitably valved to allow for any desired flow configuration. One line passed through a rotameter and control valve and finally into the top of the packed column. The second line was fed into a pump, where the pressure was boosted to 380 kPa. The wastewater then flowed through a rotameter into the jet scrubber.

Using the above mode of operation, an entire series of experiments was performed on each contactor separately. This experimental arrangement, which was essentially a batch operation, permitted the same effluent to be pumped to each ozone contactor without the need for parallel, simultaneous operation.

Pilot Plant Effluent at Robert A. Taft Laboratory

Secondary effluent was also obtained from the conventional activated sludge pilot plant located at the Robert A. Taft Laboratory building. The raw wastewater entering the plant was of mixed industrial and domestic origin. Effluent from the final clarifier was pumped through a magnetic flow meter, and the flow split between the two contactors. An optional mixed media pressure filter was available for removing suspended solids from the effluent prior to splitting the flow. Data obtained under this arrangement were collected with both contactors operating in parallel.

DESCRIPTION OF EQUIPMENT

General

All experimental work was performed at the USEPA pilot plant facility located at the Robert A. Taft Laboratory building, Cincinnati, Ohio. The ozonation system consisted of ozone generation equipment and two generic type contactors. A flow schematic of the ozone pilot system is shown in Figure 1. A block diagram is presented in Figure 2 showing a mass balance for ozone and effluent during a typical pilot run.

Nominal design flow capacity for each ozone contactor was 75 ℓ/min of secondary effluent. The ozone generator was capable of producing ozone at a maximum rate of 3500 mg/min. Since the pilot facilities were designed for evaluating two contactors in parallel, the maximum applied dosage per contactor was approximately 23 mg/ℓ.

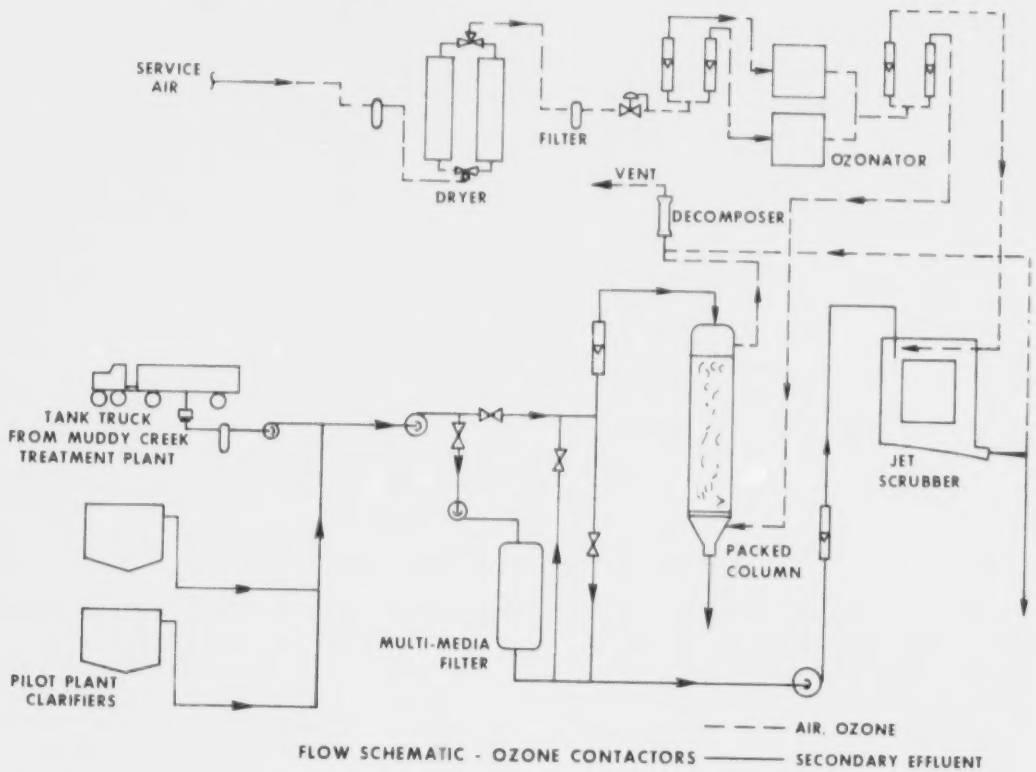


Figure 1. Schematic of Ozone Pilot Plant System

Ozone Generation

Service air from the Robert A. Taft Laboratory building, supplied at a pressure of 600 kPa, served as the source of air for ozone generation. A standby 4 kW compressor was available for air supply in the event of failure in the service air system.

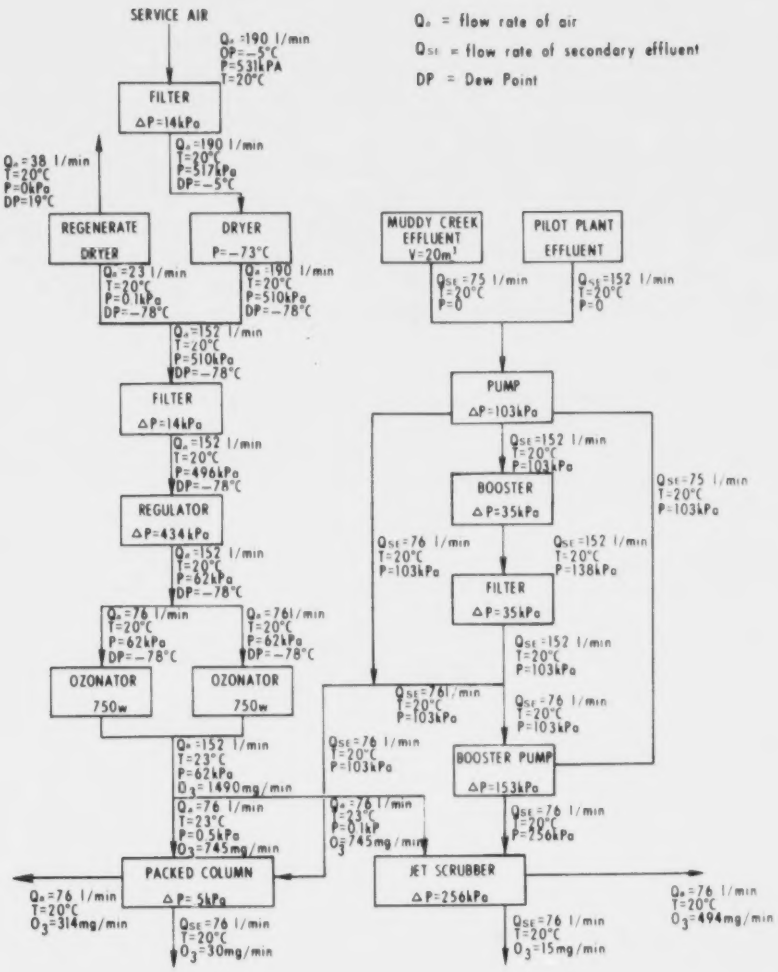


Figure 2. Mass Balance on Ozone Pilot Plant

The air was filtered for removal of particulates and lubricants, then dried by adsorption of water vapor on activated alumina. The dryer consisted of two parallel dryer beds, each containing 7.7 kg of activated alumina. The process air was passed through one of the dryer beds, where the dew point was lowered to -78 °C. Approximately 15 percent of the dried air was returned for regenerating the alumina in the other dryer bed. The dryers then automatically reversed their function, placing the regenerated bed on line for drying air while the other bed underwent regeneration. The dried air was then filtered for removal of any carry-over adsorbant and continuously monitored by an in-line dew-point meter.

The dried air was reduced in pressure from 600 kPa to 55 kPa and then split into two lines, each equipped with a rotameter and valve for flow control between 75 and 500 ℓ/min. The gas then entered the dual ozonator, which

was air-cooled and contained six plates per unit. Power was applied between 200 and 2000 watts, depending upon the ozone concentration and air flow desired for the particular experimental run. The temperature of both ozone-enriched gas streams was measured upon exiting the ozonator. The two streams were recombined to obtain a homogeneous mixture and then split before entering rotameters with a range between 20 and 130 ℓ/min. After the rotameters, seperate gas lines fed the packed column and the jet scrubber. An equipment description for pilot items is shown in Table 1.

TABLE 1. LIST OF EQUIPMENT AND SPECIFICATIONS

Description	Manufacturer	Model no.	Capacity
Prefilter	Pall Trinity Micro Corp.	MCC1001SV160	-
Dryer	Pall Trinity Micro Corp.	25HA1	700 l/min - -40 °C
Afterfilter	Pall Trinity Micro Corp.	MCC1101EC12	-
Dew point monitor	Shaw	Mini Hygrometer	-20 °C to -80 °C
Ozonator	Computerized Pollution Abatement Corp.	OZ-180-G	4 kg O_3/d
Packed column	Corning Glass	230 mm D X 3.1 m	Intalox Packing, Size: 13 mm & 25 mm
Jet scrubber	R. P. Industries	Dynactor Model DY 12-10	76 l/min
Decomposer	Chromalox	GCH330	100-350 °C
Multi-media filter	Baker Filtration Co.	HRC-30D	370 l/min
Ozone gas analyzer	Dasibi Environmental Corp.	1003-AH	-
Ozone residual analyzer	Fischer & Porter	17L2112A1	0 - 2.5 mg O_3/l

Packed Column

The packed column was a 230 mm diameter glass column 3.1 m in length. The packing consisted of either 13 mm or 25 mm ceramic intalox saddles. A teflon redistrubutor plate was located midway in the column to redirect the liquid towards the center of the column. The packing rested on a ceramic support plate at the bottom of the column. Secondary effluent entered the top of the column (Figure 3) and exited at the bottom. The residence time of the secondary effluent was 20 seconds at a flow rate of 75 ℓ/min. Ozone was injected at the bottom of the column, flowed upward and countercurrent to the secondary effluent, and exited at the top. Pressure taps were located in the gas lines at the bottom and top of the column for determining the differential gas pressure during an experimental run. A photograph of the entire packed column is shown in Figure 3.

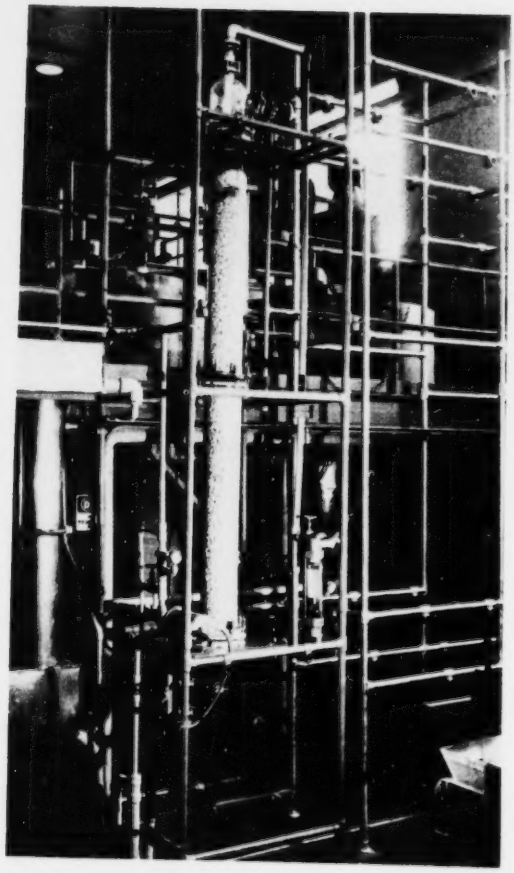


Figure 3. View of Packed Column

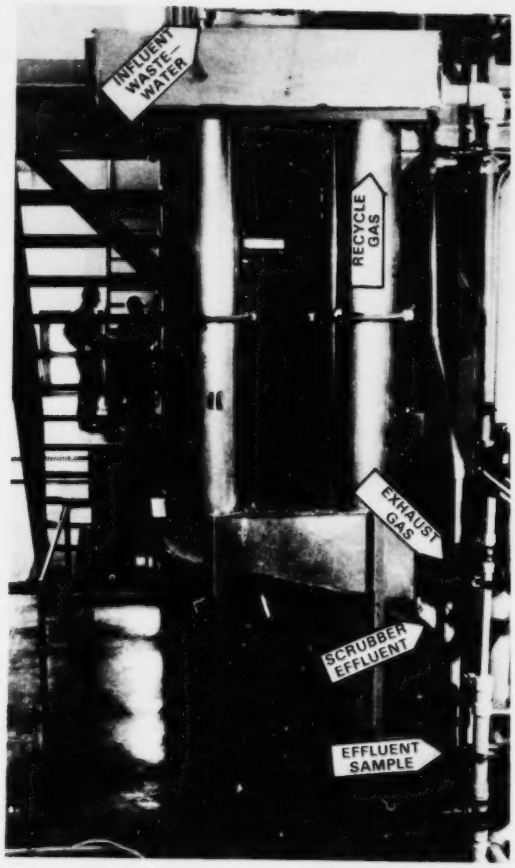


Figure 4. View of Jet Scrubber

Jet Scrubber Contactor

The jet scrubber was a stainless steel liquid-gas contactor in which secondary effluent was pumped at a pressure of 280 kPa through an orifice into a 300 mm diameter chamber. The resulting pressure drop caused minute droplets to form. The ozone entered near the orifice and both components (secondary effluent and ozone) flowed concurrently down the chamber. The combined stream then flowed to a bottom outlet where the contacting gas was separated from the effluent. A portion of the gas was aspirated back into the upper chamber by the liquid flowing through the orifice and recycled to the inlet area. A photograph of this contactor is shown in Figure 4. Figure 5 shows the action of the jet orifice producing droplets.

Ozone Decomposer

The exhaust gas from each of the contactors was directed to an ozone decomposer. An electric heater was used to increase the exit gas temperature to between 260 °C and 290 °C to insure destruction of the ozone in the off-gases. Figure 6 is a photograph of the decomposer.

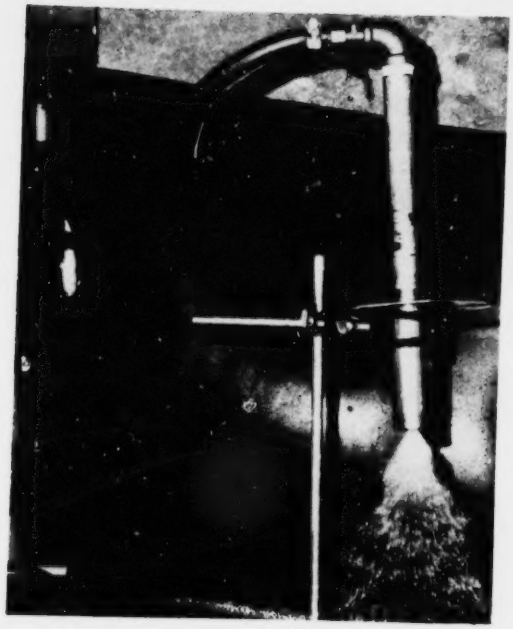


Figure 5.
Jet Action of Scrubber
(removed from contactor)

Figure 6.
View of Ozone Gas Decomposer

SAMPLE COLLECTION

Gas Samples

Ozone gas sampling ports were located at the outlet of the ozone generator, the exhaust gas line from each contactor, and the exit gas line following the ozone decomposer. Prior to sample collection the gas line was purged for approximately one minute to insure equilibrium conditions.

All gas samples were analyzed for ozone by the standard iodometric method, based on the report of Birdsall, Jenkins, and Spadinger (6). A specified dosage condition was set by collecting a grab inlet gas sample and measuring the ozone concentration iodometrically. Continuous measurement of ozone in the gas stream was made subsequent to the grab analysis to provide assurance of a steady state ozone concentration. The continuous monitoring for operating control was accomplished by a Dasibi Environmental Corporation (Glendale, California) ozone analyzer. Recalibration of the latter instrument was performed at the start of each day.

Exhaust gas samples from the ozone contactors were collected and analyzed iodometrically immediately after collection of an effluent wastewater sample.

Wastewater Effluent Samples

Valved sampling ports were located on the influent and effluent lines of both ozone contactors. Prior to actual sample collection, the sample

lines were flushed for approximately 30 seconds to make certain that any build-up of solid materials or microorganisms would be eliminated.

All samples were grab samples. Coliform MPN tubes were inoculated and ozone residuals were measured immediately after sample collection. Samples taken for physical-chemical characterization and for pathogen enumeration were preserved by refrigeration for no more than one hour, according to Standard Methods (1). Samples for chemical oxygen demand (COD) and total organic carbon (TOC) analyses were preserved by acidification with sulfuric acid and hydrocloric acid, respectively.

Samples were collected approximately 30 minutes after start-up or a change in experimental conditions. The sampling schedule was based on the flow rate such that sample collection followed the flow of a single slug of liquid through the treatment process.

OZONE CONCENTRATION

Ozone Gas Analysis

Ozone concentration in the inlet and exhaust gas was determined iodometrically (6). The ozone-air lines were first purged by allowing the gas to flow into a solution of approximately 1 N potassium iodide (KI). Following purging, the gas stream was then directed through a series of two 500 ml gas washing bottles, each containing approximately 400 ml of a 1 percent KI solution. The exit gas from the second gas washing bottle passed through a wet test meter for determination of the gas sample volume (Figure 7). The solutions in the gas washing bottles were transferred to a 1500 ml beaker and acidified to a pH of less than 2 by the addition of 20 percent sulfuric acid. This solution was titrated to the starch end point with 0.050 N sodium thiosulfate ($Na_2S_2O_3$). The titrant was standardized daily against potassium dichromate (6).

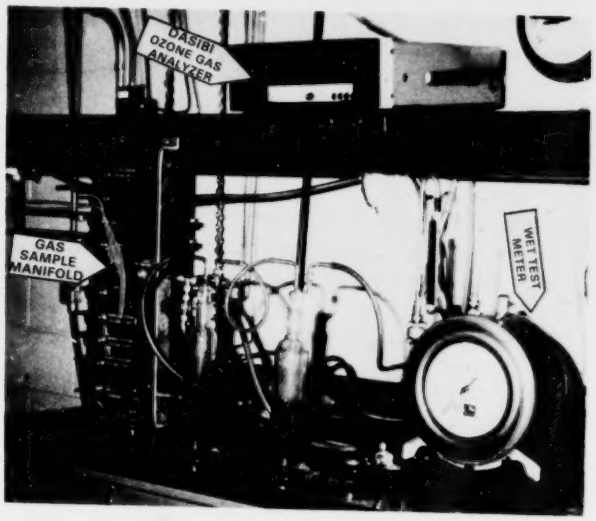


Figure 7. View of Gas Analysis Work Station

Ozone Residual Analysis

A modification of the amperometric titration method for total residual chlorine (1) was used for determination of effluent residual ozone. Samples were collected at the effluent lines of both contactors in a 200 ml sample bottle containing 1 ml of a 1 percent KI solution and 4 ml of pH 4 acetic acid-sodium acetate buffer. The sample was immediately transferred to the titration cup and titrated with 0.0050 N $Na_2S_2O_3$ to the amperometric end point. The titrant was standardized daily against a standard iodine solution.

CHEMICAL AND PHYSICAL CHARACTERIZATION OF WASTES

Total chemical oxygen demand (TCOD), soluble chemical oxygen demand (SCOD) after filtration through a Whatman glass fiber filter, total organic carbon (TOC), total suspended solids (TSS), volatile suspended solids (VSS), ammonia nitrogen (NH_4^+-N), total Kjeldahl nitrogen (TKN), manganese (Mn), iron (Fe), pH, and turbidity were determined according to the USEPA Methods Manual (15). Nitrate nitrogen (NO_3-N) and nitrite nitrogen (NO_2-N) were determined by the automated hydrazine reduction method (10).

BACTERIOLOGICAL METHODS

Samples collected for bacteriological analysis, both before and after ozonation, were mixed with sodium thiosulfate (1). Total and fecal coliforms were enumerated by the 5-tube, 4-dilution most probable number (MPN) technique (1). Presumptive medium was lactose broth (Difco), and confirmatory medium for total coliforms was brilliant green bile broth (Difco). EC broth was used as confirmatory medium for fecal coliforms. Fecal streptococci were enumerated by the membrane filter technique (1) using KF streptococcus agar (Difco). Isolation and enumeration of Salmonella spp. were performed using a modification of the Kenner and Clark Method (11) (see Appendix A for a detailed description of the method.)

STATISTICAL DATA HANDLING AND EXPERIMENTAL DESIGN

Testing of the pilot plant ozonation process was performed according to predetermined factorial arrangement. The arrangement, called a split-split-plot design, was modelled according to Anderson and McLean (4).

Secondary effluent was pumped to each ozone contactor at a rate of 75 ℓ/min, while ozone gas, generated from air at a constant concentration of 9.7 mg ozone/ℓ air, was fed to both contactors at various gas flow rates. Dosage was determined by multiplying the concentration of ozone in the inlet gas by the ratio of the gas to liquid flow rates. Four different pre-selected dosage levels were used, and grab samples of ozonated effluent from both contactors were taken for bacteriological and chemical analysis. Both contactors received the same dosage at any given time, but the order in which the four dosage levels were applied in any given experiment was randomized by referring to a random number table. Each entire experiment was considered a "whole plot" and was replicated on six different days (R_i). The "split-plot" consisted of four dosage levels (D_j)within a replicate experiment, and the "split-split-plot" consisted of the two contactors (C_k) compared at each dosage level within each replicate experiment.

Separate analysis of variance (ANOVA) were performed to compare the two contactors on the basis of six dependent variables (performance criteria) as a function of one independent variable (applied ozone dosage).

The performance criteria were log total coliform reduction, log fecal coliform reduction (log N_0/N, where N_0 = the initial number of coliform bacteria and N = the number remaining after treatment), percent ozone utilization, total ozone utilized (mg/ℓ), ozone residual (mg/ℓ), and ozone consumtion (mg/ℓ).

Applied ozone dosage was defined as follows:

$$D_0 = y_1 G/L \tag{1}$$

where D_0 = applied dosage (mg O_3/ℓ_{liq})

y_1 = ozone concentration in the inlet gas (mg O_3/ℓ_{gas})

G = gas flow rate (ℓ_{gas}/min)

L = liquid flow rate (ℓ_{liq}/min).

Percent ozone utilization was defined as follows:

$$\% = \frac{y_1 - y_2}{y_1} (100) \tag{2}$$

where y_2 = ozone concentration in the exhaust gas (mg O_3/ℓ_{gas}).

Total ozone utilization was defined as follows: (3)

$$U_o = \text{Dosage x fraction utilized} = y_1(G/L)\frac{y_1 - y_2}{y_1} = G/L\ (y_1 - y_2),$$

where U_o = total ozone utilized (mg/ℓ).

Ozone consumption was defined as follows:

$$C_o = U_o - R_o, \tag{4}$$

where C_o = consumption (mg/ℓ), and R_o = ozone residual (mg/ℓ).

In each analysis of variance (ANOVA) there were three "main effects" (i.e., C_k, D_j, and R_i) under investigation, and two "interaction effects" (i.e., R_iC_k and D_jC_k). The contactor main effect (C_k) tested the difference in performance (i.e., total or fecal coliform log reduction (TCLR or FCLR) ozone utilization, etc.) between the two contactors. The dose main effect (D_j) tested the effect of ozone dosage on the performance of both contactors.

The replication main effect (R_i) tested the effect of different days on the performance of both contactors. Since the only variable which was not controlled from day to day was effluent quality, R_i actually tested the effect of effluent quality on contactor performance. The contactor-dosage interaction effect (C_kD_j) tested whether the difference in performance between the two contactors was consistent or changed at each dosage level. Finally, the contactor-replication interaction effect (C_kR_i) tested whether the difference in performance between the two contactors was consistent or changed from day to day.

In addition to the ANOVA's described above, data were subjected to linear and stepwise multiple regression analyses to evaluate the effects of different wastewater parameters individually or in concert on the selected performance criteria. Data analyses were facilitated by an IBM 370 computer, using Biomedical Computer Programs BMDO2V (Analyses of Variance for Factorial Design) and BMDO2R (Stepwise Regression) (5).

SECTION 5

RESULTS AND DISCUSSIONS

OZONE GENERATOR OUTPUT

The ozone generator was designed to deliver 4 kg O_3/d. Initial evaluation of ozone output revealed that less than 2 kg/d were being generated. A dew point monitor was inserted into the conditioned air line following the dryer and indicated that the dew point of the air was above -20 °C. The purge rate to the dryer was increased and the dew point subsequently fell below -40 °C. This caused the ozone output from the generator to rise to the specified 4 kg/d level. No further problems were experienced in either maintaining a dew point below -40 °C or achieving the desired ozone output.

Mapping of Ozone Generator

Before initiating the contactor evaluation phase of the investigation, it was necessary to establish the relationship between electrical power, gas flow rate, and ozone concentration in the gas to permit evaluation of the ozone generation efficiency of the CPAC ozone generator under various experimental conditions. This was accomplished by mapping the ozone generator, using only one module of the dual unit to insure accurate gas flow control.

Ozone concentration in the gas was measured as a function of electrical power at various gas flow rates. Power was ajusted from 0.25 to 2.0 kw at 0.25 kw increments. Results are shown in Figure 8. At a constant gas flow rate, ozone concentration increased with power until a plateau was reached. After this point, further increase in power actually resulted in a reduction in ozone concentration.

The data from Figure 8 were rearranged to illustrate ozone production, in terms of kg/h, as a function of gas flow at various power levels. Results are shown in Figure 9. It is evident that ozone production increased with gas flow rate, followed by a declining production as optimum gas flows were exceeded, except at the 0.25 kw power level.

The data were again rearranged to demonstrate the power requirements necessary to produce a unit weight of ozone as a function of gas flow rate at specified power levels. Results are presented in Figure 10. It is clear that, at low gas flow rates, considerably more energy was required to generate a unit weight of ozone than at higher flow rates.

The above mapping experiment can provide useful information to the

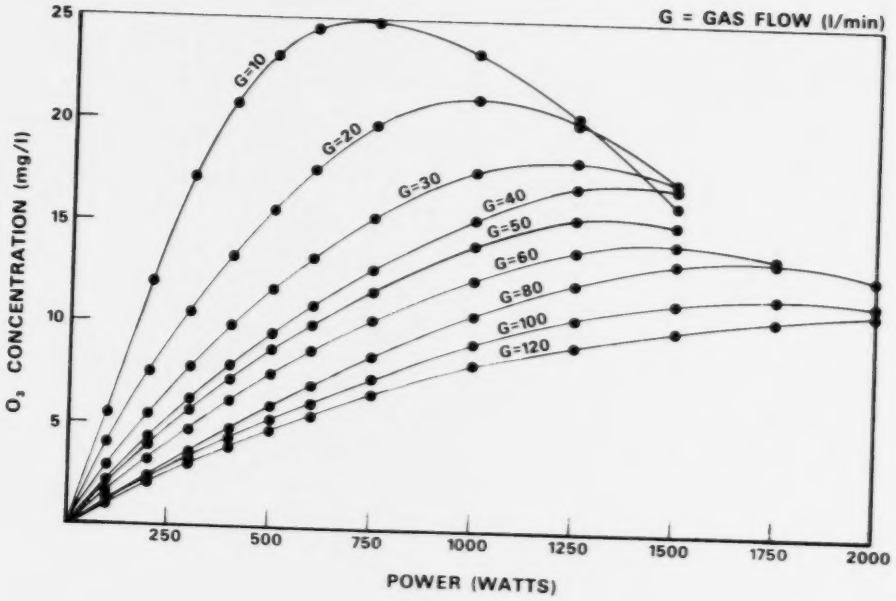
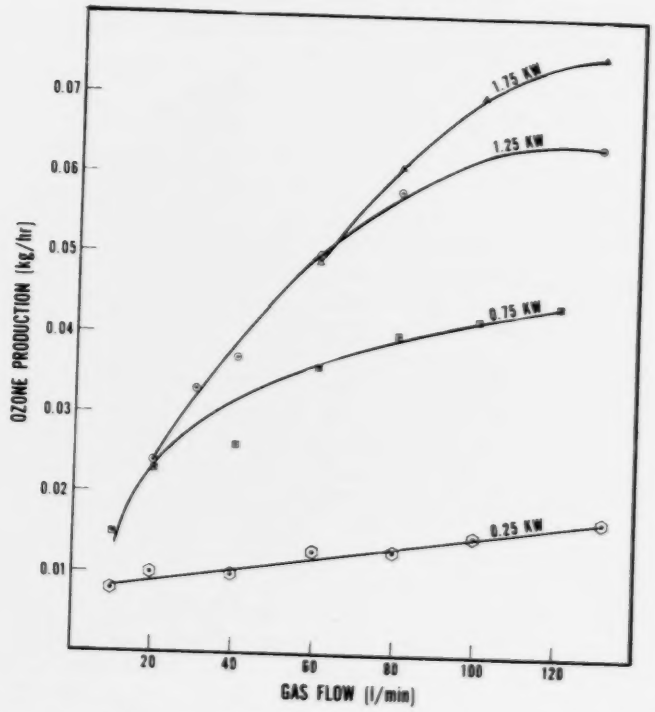


Figure 8. Relationship Between Power Consumption and Ozone Concentration



igure 9. Effect of Gas Flow Rate on Ozone Production

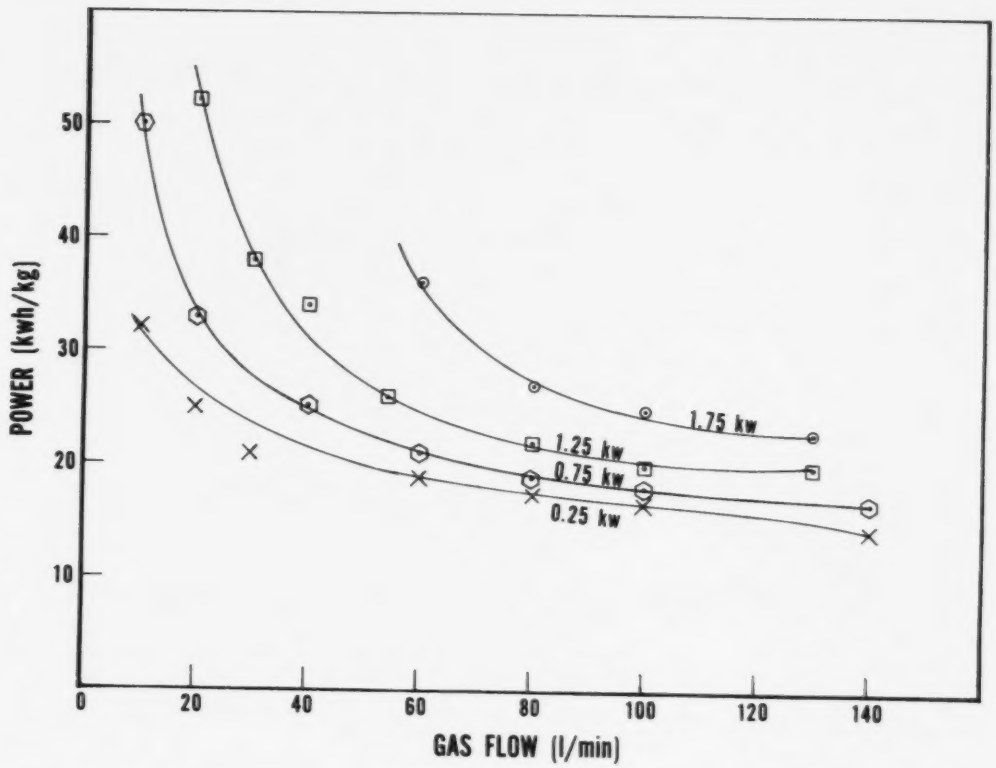


Figure 10. Effect of Gas Flow Rate on Power Consumption

design engineer in sizing ozone generator equipment and to the plant operator in selecting an operating condition that would deliver the required ozone capacity at the minimum power requirement per unit weight of ozone. Thus, to maximize ozone production (kg per unit time) higher gas flows are needed (Figure 9), resulting in improved power efficiency (Figure 10). However, higher power levels are also needed (Figure 9), thereby offsetting the improved production efficiency by a greater energy usage per kg ozone (Figure 10). Conversely, to maximize the ozone concentration, lower gas flows are needed (Figure 8), resulting in increased power per kg ozone produced (Figure 10) and lower ozone production in terms of kg per unit time (Figure 9).

PHASE 1 - BATCH OPERATIONAL MODE

In this phase of the investigation, experiments were performed on wastewater effluent which was transported by truck from the Muddy Creek Wastewater Treatment Plant (MCWTP). Since the effluent was a batch source not subject to continual change in quality, experiments were conducted on each contactor separately rather than in parallel.

Wastewater Effluent Characteristics

Table 2 summarizes the mean, standard deviation, and range of the effluent characteristics of the Muddy Creek effluent from August 2, 1976, to November 2, 1978, the experimental period for this phase of the study.

It is evident that the levels of TSS, turbidity, and TOC were low, and there was very little difference between TCOD and SCOD. Most of the TKN was composed at NH_4^+-N. In general, the MCWTP effluent quality was excellent.

TABLE 2. SUMMARY OF MUDDY CREEK EFFLUENT CHARACTERISTICS

Parameter	Mean	Standard Deviation	Range
Temperature (C)	21	3	14-24
TCOD, mg/ℓ	30	10	18-56
SCOD, mg/ℓ	24	9	15-49
TOC, mg/ℓ	10.3	5.2	4.4-25.5
TSS, mg/ℓ	6.7	3.8	2.4-20
TURB, JTU	3.8	1.5	2.3-7.6
TKN, mg/ℓ	8.3	8.2	1.9-37.8
NH_4^+-N, mg/ℓ	7.2	7.6	0.1-34
ORG-N, mg/ℓ	1.6	1.0	0.2-3.8
Log total coliform density	5.77	0.51	4.90-6.73
Log fecal coliform density	5.38	0.64	4.36-6.54
Log fecal streptococci density	4.19	0.71	2.70-5.23

Determination of Mass Transfer Coefficients

Mass transfer coefficients in the packed column and jet scrubber were determined using MCWTP effluent. Gas flow rates were varied between 35 and 150 ℓ/min. Ozone was measured in the inlet and exhaust gases and in the liquid emerging from the contactors.

The quantity of ozone that could be absorbed by the secondary effluent was limited by the inlet ozone gas concentration as related to Henry's law. This relationship is described by the following equation:

$$y^* = Hx \qquad (5)$$

where y^* = partial pressure of ozone in the gas in equilibrium with the dissolved ozone in the liquid (mm Hq)

H = Henry's constant (mm Hg/mol fraction of ozone in the liquid)

m = mol fraction of ozone in the secondary effluent (mols O_3/mol liquid).

Henry's constant defining the relationship between the partial pressure of ozone and the concentration of ozone in the liquid can be obtained from the International Critical Tables (16). Since the units of the terms in equation 5 were tedious to manipulate, they were converted to the following more useful terms by incorporating relationships defined in the gas laws:

y^* = concentration of ozone in the gas in equilibrium with ozone in the liquid (mg O_3/litre gas),

H = litres of liquid/litre of gas,

x = concentration of ozone in the liquid (mg O_3/litre liquid).

The magnitude of Henry's constant is substantially affected by temperature, as shown in Figure 11. As temperature increases, the value of Henry's constant increases.

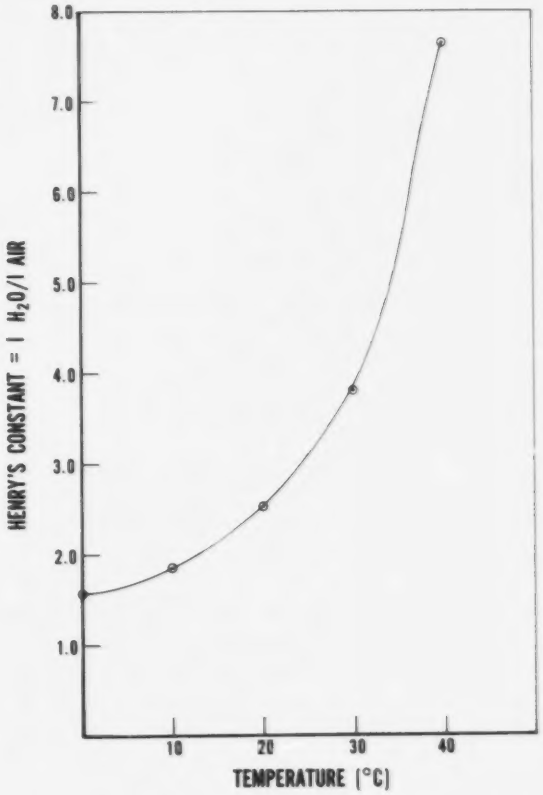


Figure 11. Variation of Henry's Constant with Temperature

The mass transfer coefficients for the packed column were determined using the following equation:

$$N = G\ (y_1 - y_2) - KgVa\ (\Delta\ y_{1m}) \tag{6}$$

where N = ozone transferred from the gas phase into the secondary effluent (mg/min),

G = gas flow rate (litres gas/min),

y_1 = ozone concentration in the inlet gas (mg/ℓ),

y_2 = ozone concentration in the exhaust gas (mg/ℓ),

KgVa = overall mass transfer coefficient (litres gas/min),

Δy_{1m} = log mean concentration difference of ozone in the gas phase across the entire column (mg/ℓ)

The term Δy_{1m} is defined by the following equation:

$$\Delta y_{1m} = \frac{(y_1 - y_1^*) - (y_2 - y_2^*)}{\ln \frac{(y_1 - y_1^*)}{(y_2 - y_2^*)}} \tag{7}$$

where y_1^* = ozone concentration (mg/ℓ) in the gas phase in equilibrium with the ozone residual in the liquid at the bottom of the column, as defined by Henry's Law (equation 5),

and y_2^* = ozone concentration (mg/ℓ) in the gas phase in equilibrium with the ozone residual in the liquid at the top of the column.

In the packed column, $y_2^* = 0$ because there was no ozone residual in the liquid entering the top of the column. Thus, equation 7 simplifies to:

$$y_{1m} = \frac{(y_1 - y_1^*) - y_2}{\ln \frac{(y_1 - y_1^*)}{y_2}} \tag{8}$$

The mass transfer coefficients for the jet scrubber were computed in the same manner. However, since the flow configuration in the jet scrubber was concurrent rather than countercurrent, $y_1^* = 0$ because the liquid entering the contactor contained no ozone residual. Thus, for the jet scrubber, equation 7 simplifies to :

$$\Delta y_{1m} = \frac{y_1 - (y_2 - y_2^*)}{\ln \frac{y_1}{(y_2 - y_2^*)}} \tag{9}$$

Detailed results from these experiments are given in Appendix B. The mass transfer coefficients for both contactors at various flow rates are illustrated in Figure 12. The data indicate that the mass transfer coefficients for the packed column were more than twice the value determined for the jet scrubber at the gas flow rates studies.

Henry's Law states, by definition, that as ozone residual increases, ozone concentration in the gas phase in equilibrium with the residual also increases. This means that transfer is inhibited by high ozone residuals. A countercurrent flow configuration, such as in the packed column, has the advantage not only of contacting the liquid containing the highest ozone residual with the gas containing the highest ozone concentration (i.e., at the bottom of the column), but also of contacting the liquid containing the least ozone residual with the gas containing the lowest concentration of ozone (i.e., at the top of the column). This tends to equalize the concentration driving force and mass transfer rate across the entire length of the column.

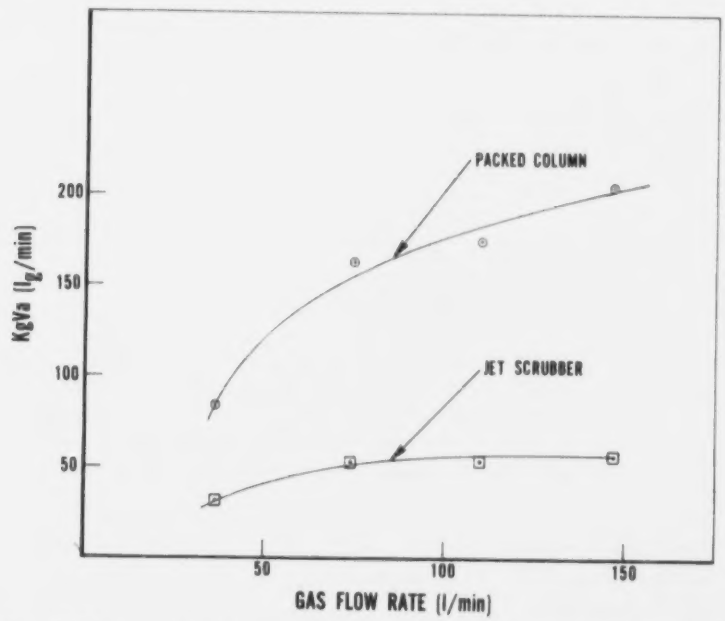


Figure 12. Effect of Gas Flow Rate on Mass Transfer Coefficient

In contrast, the jet scrubber, which operates in a concurrent flow configuration, maintains a high concentration gradient at the inlet end. As the residual increases, the exit gas concentration, which must be in equilibrium with the residual, also increases. This substantially limits the concentration driving force in the jet scrubber and explains the lower mass transfer coefficients relative to those of the packed column.

Both contactors had relatively short contact times (approximately 20 seconds for the packed column and 3 seconds for the jet scrubber, at a liquid flow rate of 75 ℓ/min). This tended to hinder both mass transfer and ozone utilization. Longer contact times would permit the dissolved ozone to react with oxidizable constituents in the secondary effluent, lowering the ozone residual and increasing the overall ozone concentration driving force.

Ozone Utilization

Ozone utilization, as defined earlier, was evaluated in both contactors from the same data base used to compute the mass transfer coefficients.

The quantity of ozone that can be absorbed by water is limited by the temperature of the water and the concentration of the ozone in the gas stream. Thus, the maximum ozone residual that can be obtained in water is fixed by Henry's Law (equation 5). However, the results from experiments with secondary effluent revealed that ozone transfer was greater than could be predicted by Henry's Law. The demand of the secondary effluent created by the presence of oxidizable organic and inorganic compounds enabled more ozone to be transferred to the wastewater.

Figure 13 summarizes the percent ozone utilization data in both contactors as a function of applied ozone dose. Results indicate that the percent ozone utilized by the packed column was substantially greater than the jet scrubber. Thus, the packed column was superior to the jet scrubber from the standpoint of mass transfer efficiency and percent ozone utilization efficiency.

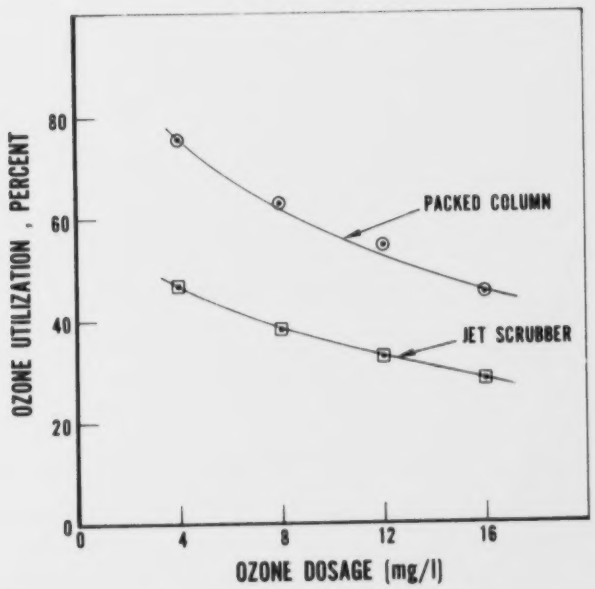


Figure 13. Effect of Ozone Dosage on Percent Ozone Utilization

Ozone Dosage

Dosage was defined earlier in equation (1): $D_o = y_1 G/L$.

There are two ways to vary ozone dosage: (1) change the G/L ratio while maintaining a constant gas concentration, or (2) change the ozone gas concentration while maintaining a constant G/L ratio. However, utilization can be changed by maintaining dosage constant and increasing the concentration of ozone in the gas (i.e., increase y_1 and decrease G/L). Figure 14 illustrates the change in percent ozone utilization in both contactors as a function of G/L at a constant dosage level. It is clear that as G/L increased (or y_1 decreased), percent ozone utilization decreased, even though the applied dosage was constant. Caution must be exercised in using these data, because increased y_1 values require increased power input per unit weight of ozone when the dosage is constant (see Figures 8 and 9). Thus, power must be factored into any evaluation to establish optimum performance criteria. The most cost-effective operating condition for ozone disinfection does not necessarily comprise the lowest ozone dosage.

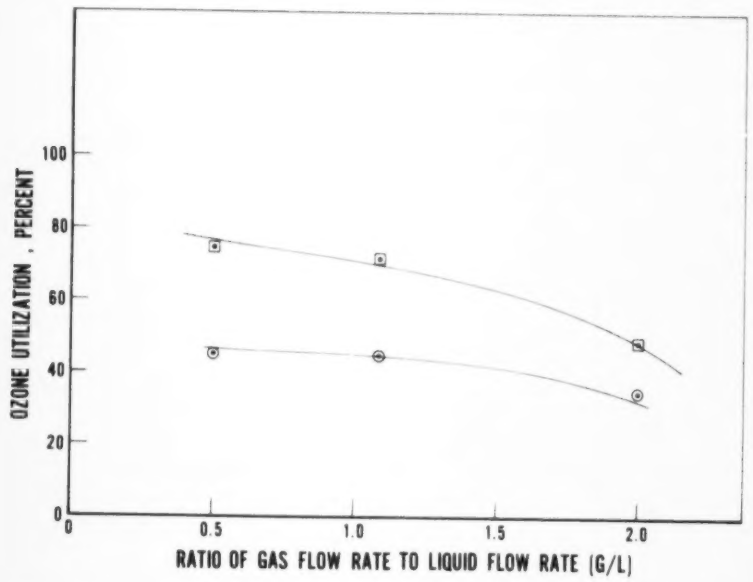


Figure 14. Effect of G/L Ratio on Percent Ozone Utilization at a Constant Dosage of 8.0 mg/ℓ

Effect of Packing Size on Packed Column Performance

After completing Phase I of the investigation, it was necessary to switch from the MCWTP effluent to the R.A. Taft Laboratory building pilot plant effluent so that both contactors could be operated in parallel. The overall quality of the latter effluent was inferior to the MCWTP effluent. This factor resulted in excessive pressure drops in the packed column when the system was operated at a liquid flow rate of 75ℓ/min.

To compensate for the increased pressure drops in the packed column, it was necessary to increase the packing size from 13 mm to 25 mm ceramic intalox saddles. This modification, in effect, lowered the surface area of the packing and consequently enabled operation of the column at more reasonable pressure drops (i.e., <300 mm H_2O). However, this also affected the mass transfer efficiency of the column. Table 3 demonstrates the effect of packing size on the overall mass transfer coefficients of the packed column at various gas flow rates.

The overall mass transfer coefficient (KgVa) consists of the product of the mass transfer coefficient (KgV) and the surface area per unit volume of packing (a). Although the KgVa did not substantially change with packing size, the total mass transfer of ozone into the liquid over the entire column decreased as a direct result of the decrease in surface area of the packing.

TABLE 3. EFFECT OF PACKING SIZE ON OVERALL MASS TRANSFER COEFFICIENTS (Kg Va) OF THE PACKED COLUMN AT VARIOUS GAS FLOW RATES

Gas flow rate, ℓ/min	Kg Va, ℓ gas/min	
	13 mm packing (KgV, ℓ/min/m)	25 mm packing (KgV, ℓ/min/m)
37	84 (0.135)	46 (0.180)
74	163 (0.261)	66 (0.258)
110	175 (0.280)	73 (0.285)
147	205 (0.329)	86 (0.336)

Contactor Performance

Total Coliform Reduction--

During the three month period between August 2, 1976, to November 2, 1976, a total of 40 experiments were performed with MCWTP effluent to evaluate the total coliform reduction efficiency of the packed column and the jet scrubber. The data were grouped into three segments according to the magnitude of the applied ozone dosage (i.e., low, moderate, and high). All observations were taken in matched pairs to facilitate direct comparison between the two contactors. The t-test for matched pairs was performed according to Natrella (17) after confirming that the data were normally distributed. A significance level (2) of 0.05 was chosen for all tests. The data are summarized in Table 4.

TABLE 4. DIFFERENCE IN TOTAL COLIFORM LOG REDUCTION (TCLR) BETWEEN THE PACKED COLUMN AND JET SCRUBBER AS A FUNCTION OF APPLIED DOSAGE (MCWTP EFFLUENT)

Ozone dosage, mg/ℓ			Number of data points	Mean TCLR (Std. dev.)		Mean difference		t
Level	Range	Mean	(n)	Packed column	Jet scrubber	(Std. dev.)	t	(α=0.05)
Low	2.4- 4.6	3.6	14	1.99 (0.63)	1.36 (0.87)	0.63 (0.77)	3.06	2.16
Mod-erate	5.9-10.0	7.5	18	2.77 (0.59)	2.32 (0.64)	0.45 (0.52)	3.67	2.11
High	11.8-18.6	13.9	8	2.41 (0.96)	2.21 (0.92)	0.21 (0.53)	1.12	2.36
All	2.4-18.6	7.4	40	2.43 (0.76)	1.96 (0.89)	0.46 (0.62)	4.69	2.02

The t-statistics in Table 4 and subsequent tables were calculated from the following equation (17):

$$t = \frac{\bar{x}_d \, n}{S_d} \qquad (10)$$

where $\bar{x}_d$ = mean difference in TCLR between contactors, S_d = standard deviation of the difference, and n = number of data points. It is clear that total coliform reduction was significantly greater in the packed column than in the jet scrubber at the low and moderate dosage levels but not at the high dosage level. When considering all dosage levels combined (n = 40), TCLR in the packed column was significantly greater than that in the jet scrubber.

Fecal Coliform Reduction--

The fecal coliform data were analyzed similarly and summarized in Table 5. The fecal coliform data reflect the same trends as the total coliform data. The packed column significantly outperformed the jet scrubber with respect to fecal coliform reduction at low and intermediate dosage levels but not at the high dosage level. When considering all dosage levels, the packed column was significantly better than the jet scrubber with respect to FCLR.

TABLE 5. DIFFERENCE IN FECAL COLIFORM LOG REDUCTION (FCLR) BETWEEN THE PACKED COLUMN AND JET SCRUBBER AS A FUNCTION OF APPLIED DOSAGE (MCWTP EFFLUENT)

Ozone dosage, mg/ℓ			Number of data points	Mean FCLR (Std. dev.)		Mean difference		t
Level	Range	Mean	(n)	Packed column	Jet scrubber	(Std. dev.)	t	(α=0.05)
Low	2.6- 4.6	3.6	13	2.28 (1.27)	1.42 (1.15)	0.86 (1.10)	2.82	2.18
Mod-erate	5.9-10.0	7.5	17	3.27 (1.12)	2.76 (1.09)	0.51 (0.86)	2.45	2.12
High	11.8-18.6	14.0	8	3.09 (1.33)	2.53 (0.90)	0.56 (0.98)	1.62	2.36
All	2.6-18.6	7.5	38	2.89 (1.27)	2.25 (1.21)	0.64 (0.98)	4.02	2.03

Fecal Streptococcus Reduction--

The difference in efficiency between the two ozone contactors with respect to fecal streptococcus reduction are presented in Table 6. It is clear that the packed column significantly outperformed the jet scrubber with respect to fecal streptococcus reduction at all dosage levels studied.

TABLE 6. DIFFERENCE IN FECAL STREPTOCOCCUS LOG REDUCTION (FSLR) BETWEEN THE PACKED COLUMN AND JET SCRUBBER AS A FUNCTION OF APPLIED DOSAGE (MCWRTP EFFLUENT)

Ozone dosage, mg/ℓ			Number of data points	Mean FSLR (Std. dev.)		Mean difference		
Level	Range	Mean	(n)	Packed column	Jet scrubber	(Std. dev.)	t	t (α=0.05)
Low	2.6- 5.8	3.4	10	1.63 (0.40)	1.36 (0.57)	0.27 (0.28)	3.05	2.26
Mod-erate	6.0- 8.6	7.3	13	2.65 (0.67)	2.28 (0.86)	0.37 (0.33)	4.04	2.18
High	10.0-14.6	12.7	6	3.12 (0.48)	2.17 (0.65)	0.95 (0.60)	3.88	2.57
All	2.4-14.6	7.1	29	2.39 (0.80)	1.94 (0.83)	0.45 (0.45)	5.39	2.05

Salmonella Reduction--

Attempts were made to quantify the density of Salmonella spp. before and after the ozone contactors to evaluate the disinfection efficiency of both contactors with respect to enteric pathogens. The method involves a 3-tube MPN procedure (see Appendix A) and is limited in precision and accuracy. A total of 20 samples were analyzed for Salmonella spp. in the MCWTP effluent entering the ozone contactors, plus an additional 39 matched pair samples exiting the contactors. The geometric mean Salmonella density in the 20 samples of MCWTP effluent entering the contactors was only 180 organisms/10 liters. Many of the samples from the ozone contactors contained too few numbers to measure. The data are summarized in Table 7.

Of the 39 total samples from each contactor analyzed for Salmonella spp., 28 from the packed column and 24 from the jet scrubber contained insufficient numbers to quantify as signified by the "<" symbol. Thus, it is virtually impossible to quantitatively assess the Salmonella reduction efficiency of either contactor.

Ozone Utilization--

Ozone utilization data were analyzed in the same manner as the bacteriological data. Results are summarized in Table 8.

It is clear from Table 8 that ozone utilization in the packed column was significantly higher than the jet scrubber at all dosage levels studied. In addition, the difference in utilization appeared to increase with increasing dosage. Thus, the packed column was a more efficient ozone contactor than the jet scrubber with respect to total ozone utilized, and the relative efficiency increased with increasing dosage.

TABLE 7. DENSITIES OF SALMONELLA SPP. BEFORE AND AFTER THE OZONE CONTACTORS (MCWTP EFFLUENT)

O_3 Dose, mg/ℓ	Influent No./10 liters	Effluent No./10 liters	
		Packed column	Jet scrubber
2.5	18.2	<6	7.2
2.8	280	7.2	7.2
3.0	280	<6	480
3.6	7.2	<6	<6
3.6	7.2	<6	<6
3.6	7.2	<6	<6
3.6	2300	<300	360
3.8	86	7.2	<6
3.8	18.2	<6	7.2
6.0	7.2	<6	<6
6.0	86	<6	<6
6.4	1900	18.2	18.2
6.9	780	6	18.2
7.2	2300	<300	<300
7.4	730	<300	<300
7.4	15000	360	<300
7.5	7.2	<6	<6
7.5	1280	7	18
7.6	7.2	<6	<6
7.8	480	<6	<6
7.9	480	46	<6
7.9	1280	<4	7
7.9	1900	<6	86
8.0	480	7.2	7.2
8.6	480	<6	<6
10.0	780	<6	18.2
11.2	360	<300	<300
12.0	2300	<300	<300
12.0	15000	<300	<300
12.4	42	<3.6	7.2
13.2	920	920	2200
13.5	42	<3.6	18
14.2	7.0	<6	<6
14.2	46	<6	<6
14.2	150	<6	<6
14.5	7.0	<6	<6
14.5	46	<6	<6
14.8	150	72	<6
17.7	920	186	420

TABLE 8. DIFFERENCE IN OZONE UTILIZATION BETWEEN THE PACKED COLUMN AND JET SCRUBBER AS A FUNCTION OF APPLIED DOSAGE (MCWTP EFFLUENT)

Ozone dosage, mg/ℓ Level	Range	Mean	Number of data points (n)	Mean ozone utilization, mg/ℓ (Std. dev.) Packed column	Jet scrubber	Mean difference (Std. dev.)	t	t (α=0.05)
Low	2.4- 4.6	3.6	14	2.9 (0.6)	1.7 (0.3)	1.2 (0.6)	8.1	2.16
Mod-erate	5.9-10.0	7.5	18	5.3 (1.0)	3.1 (1.0)	2.2 (1.1)	8.3	2.11
High	11.9-18.6	13.9	8	7.4 (1.6)	4.0 (1.2)	3.4 (1.8)	5.2	2.36
All	2.4-18.6	7.4	40	4.9 (2.0)	2.8 (1.2)	2.1 (1.4)	9.6	2.02

Ozone Consumption--

The contactors were also evaluated with respect to ozone consumption (i.e., utilization minus residual). Table 9 summarizes these data.

It is evident that ozone consumption in the packed column was significantly higher than in the jet scrubber at all dosage levels studied. Also, the difference in consumption between the contactors increased with dosage, just as did the difference in utilization (Table 8). The pattern expressed by the change in ozone utilization and consumption as a function of dosage was consistent.

TABLE 9. DIFFERENCE IN OZONE CONSUMPTION BETWEEN THE PACKED COLUMN AND JET SCRUBBER AS A FUNCTION OF APPLIED DOSAGE (MCWTP EFFLUENT)

Ozone dosage, mg/ℓ Level	Range	Mean	Number of data points (n)	Mean ozone consumption, mg/ℓ (Std. dev.) Packed column	Jet scrubber	Mean difference (Std. dev.)	t	t (α=0.05)
Low	2.4- 4.6	3.6	14	2.0 (0.5)	1.3 (0.4)	0.7 (0.7)	3.8	2.16
Mod-erate	5.9-10.0	7.5	18	3.6 (0.9)	2.3 (1.0)	1.4 (1.4)	4.2	2.11
High	11.8-18.6	13.9	8	5.2 (1.4)	3.0 (1.3)	2.2 (1.9)	3.3	2.36
All	2.4-18.6	7.4	40	3.4 (1.5)	2.1 (1.1)	1.3 (1.4)	6.0	2.03

Ozone Residual--

Table 10 summarizes the differences between the two contactors with respect to ozone residual as a function of dosage. Not only was the ozone residual in the packed column significantly higher than the corresponding residual in the jet scrubber at each dosage level, but also the difference in residual between the two contactors increased with higher dosages.

TABLE 10. DIFFERENCE IN OZONE RESIDUAL BETWEEN THE PACKED COLUMN AND JET SCRUBBER AS A FUNCTION OF APPLIED DOSAGE (MCWTP EFFLUENT)

Level	Ozone dosage, mg/ℓ Range	Mean	Numer of data points (n)	Mean ozone residual, mg/ℓ (Std. dev.) Packed column	Jet scrubber	Mean difference (Std. dev.)	t	t (α=0.05)
Low	2.4- 4.6	3.6	14	0.8 (0.4)	0.3 (0.2)	0.5 (0.3)	6.4	2.16
Mod-erate	5.9-10.0	7.5	18	1.7 (0.5)	0.8 (0.6)	0.8 (0.6)	5.8	2.11
High	11.8-18.6	15.9	8	2.2 (0.6)	1.0 (0.5)	1.2 (0.3)	11.4	2.36
All	2.4-18.6	7.4	40	1.5 (0.7)	0.7 (0.5)	0.8 (0.5)	9.6	2.02

Summary of Contactor Performance--

From the foregoing data analyses, it is clear that the packed column significantly outperformed the jet scrubber with respect to coliform reduction efficiency and mass transfer efficiency. Total coliform density, fecal coliform density, and fecal streptococcus density were all reduced to a significantly greater extent in the packed column than in the jet scrubber. When considering each individual dosage level, the packed column was superior to the jet scrubber with respect to total and fecal coliform reduction at low and intermediate dosages but not at the high dosage. However, fecal streptococcus reductions were significantly higher in the packed column at each dosage level studied.

Ozone utilization, consumption, and residual were significantly higher in the packed column than in the jet scrubber at all dosage levels studied, and these differences increased in magnitude with increasing dosage.

Regression Analyses

The data from the above experiments were subjected to linear regression analyses to determine which factors in the effluent contributed to the variation in the microorganism reduction efficiency data and mass transfer efficiency data. One parameter, such as log total coliform reduction, was chosen as a dependent variable and regressed individually against a number of independent variables (i.e., TCOD, SCOD, TOC, TSS, turbidity, TKN, NH_4-N, and organic-N). This was also done for log fecal coliform reduction, log fecal streptococcus reduction, ozone utilization, ozone consumption, and ozone residual as the dependent variables. No correlations were found between the

dependent variables and any of the independent variables mentioned. It was concluded that the effluent quality was sufficiently constant that the variation observed in any of the dependent variables could not be accounted for by the variation of the individual physical-chemical characteristics of the wastewater effluent.

Attempts were then made to deter ine whether bacterial reduction (TCLR, FCLR, and FSLR) could be correlated with ozone dosage, utilization, consumption, and/or residual in each contactor. A fifth variable, initial bacterial density, was also included as an independent variable. Tables 11 to 16 summarize the correlation matrices resulting from these analyses.

Tables 11 to 13 summarize the correlation between total coliform log reduction (TCLR), fecal coliform log reduction (FCLR), and fecal strep log reduction (FSLR), respectively, in the packed column and the various independent variables mentioned above. Correlations among the variables themselves are also presented.

In Tables 11, 12, 14, and 15, a correlation coefficient greater than 0.275 or less than -0.275 is significantly different from zero at the 95 percent confidence level (as determined by the t-test). In tables 13 and 16, an r-value greater than 0.33 or less than-0.33 is significantly different from zero.

As expected, significant positive correlations existed among the four ozone variables. Weak but statistically significant correlations existed between TCLR, FCLR, or FSLR and ozone dosage, residual consumption, and utilization. Thus, as any one of the latter variables increased in magnitude, there was a corresponding increase in bacterial reduction. Finally, there was statistically significant correlations between TCLR and initial total coliform density, FCLR and initial fecal coliform density, and FSLR and initial fecal streptococcus density. Thus, the higher the initial bacterial density, the higher was the resulting log reduction.

Several regression equations for the packed column were derived from the data used to construct Tables 11 to 13 and are given as follows:

$$C_o = 0.3\ D_o + 1.1 \tag{11}$$

$$U_o = 0.4\ D_o + 1.7 \tag{12}$$

$$R_o = 0.1\ D_o + 0.5 \tag{13}$$

where C_o = ozone consumption (mg/ℓ), U_o= ozone utilization (mg/ℓ), R_o= ozone residual (mg/ℓ), and D_o = ozone dosage (mg/ℓ).

Tables 14 to 16 summarize the correlations between TCLR, FCLR, and FSLR, respectively, in the jet scrubber and the various selected independent variables.

The most significant trends observable in the jet scrubber are quite different from those seen in the packed column. For example, among the ozone

variables, residual did not correlate at all with consumption. This was because the residual was very low most of the time and thus most of the ozone utilized in the jet scrubber was consumed by the effluent. The strongest correlations with bacterial reductions were initial bacterial densities and ozone residuals. Ozone dosage weakly correlated with microorganism reduction, but neither ozone consumption nor ozone utilization correlated at all. Thus, it appears that the only time significant microorganism reduction occurred in the jet scrubber was when an ozone residual was present.

A relationship derived from the data used to construct Tables 14 to 16 is given as follows:

$$R_o = 0.07\ D_o + 0.1 \qquad (14)$$

TABLE 11. CORRELATION OF TOTAL COLIFORM LOG REDUCTION (TCLR) IN THE PACKED COLUMN WITH OZONE DOSAGE, UTILIZATION, CONSUMPTION, RESIDUAL, AND INITIAL TOTAL COLIFORM DENSITY (MCWTP EFFLUENT)

	Correlation coefficient (r)*					
	O_3 Dose	Residual	Utilization	Consumption	Initial TC density	TCLR
Dose	1.000	0.725	0.869	0.823	0.299	0.519
Residual		1.000	0.806	0.608	0.225	0.339
Utilization			1.000	0.960	0.380	0.519
Consumption				1.000	0.403	0.535
Initial TC density					1.000	0.541
TCLR						1.000

* 40 data points used to derive each r-value

TABLE 12. CORRELATION OF FECAL COLIFORM LOG REDUCTION (FCLR) IN THE PACKED COLUMN WITH OZONE DOSAGE, UTILIZATION, CONSUMPTION, RESIDUAL, AND INITIAL FECAL COLIFORM DENSITY (MCWTP EFFLUENT)

	Correlation coefficients (r)*					
	Dose	Residual	Utilization	Consumption	Initial FC density	TCLR
Dose	1.000	0.718	0.866	0.821	0.322	0.326
Residual		1.000	0.800	0.603	0.302	0.414
Utilization			1.000	0.961	0.476	0.543
Consumption				1.000	0.494	0.531
Initial FC density					1.000	0.596
FCLR						1.000

*38 data points used to derive each r-value

TABLE 13. CORRELATION OF FECAL STREP LOG REDUCTION (FSLR) IN THE PACKED COLUMN WITH OZONE DOSAGE, UTILIZATION, CONSUMPTION, RESIDUAL, AND INITIAL FECAL STREP DENSITY (MCWTP EFFLUENT)

	Correlation coefficients (r)*					
	Dose	Residual	Utilization	Consumption	Initial TC density	FSLR
Dose	1.000	0.763	0.888	0.827	0.374	0.713
Residual		1.000	0.817	0.605	0.286	0.597
Utilization			1.000	0.953	0.332	0.706
Consumption				1.000	0.309	0.664
Initial FS density					1.000	0.845
FSLR						1.000

* 29 data points used to derive each r-value

TABLE 14. CORRELATION OF TOTAL COLIFORM LOG REDUCTION (TCLR) IN THE JET SCRUBBER WITH OZONE DOSAGE, UTILIZATION, CONSUMPTION, RESIDUAL, AND INITIAL TOTAL COLIFORM DENSITY (MCWTP EFFLUENT)

	Correlation coefficients (r)*					
	Dose	Residual	Utilization	Consumption	Initial TC density	TCLR
Dose	1.000	0.553	0.732	0.548	0.297	0.360
Residual		1.000	0.440	0.007	0.549	0.519
Utilization			1.000	0.901	0.108	0.212
Consumption				1.000	-0.146	-0.015
Initial TC density					1.000	0.649
TCLR						1.000

* 40 data points used to derive each r-value

TABLE 15. CORRELATION OF FECAL COLIFORM LOG REDUCTION (FCLR) IN THE JET SCRUBBER WITH OZONE DOSAGE, UTILIZATION, CONSUMPTION, RESIDUAL, AND INITIAL FECAL COLIFORM DENSITY (MCWTP EFFLUENT)

	Correlation coefficients (r)*					
	Dose	Residual	Utilization	Consumption	Initial FC density	FCLR
Dose	1.000	0.543	0.728	0.546	0.316	0.418
Residual		1.000	0.432	-0.001	0.608	0.620
Utilization			1.000	0.901	0.232	0.254
Consumption				1.000	-0.035	-0.016
Initial FC density					1.000	0.708
FCLR						1.000

*38 data points used to derive each r-value

TABLE 16. CORRELATION OF FECAL STREP LOG REDUCTION (FSLR) IN THE JET SCRUBBER WITH OZONE DOSAGE, UTILIZATION, CONSUMPTION, RESIDUAL, AND INITIAL FECAL STREP DENSITY (MCWTP EFFLUENT)

	Correlation coefficients (r)*					
	Dose	Residual	Utilization	Consumption	Initial FS density	FSLR
Dose	1.000	0.568	0.672	0.483	0.370	0.332
Residual		1.000	0.525	0.080	0.605	0.707
Utilization			1.000	0.890	0.054	0.268
Consumption				1.000	-0.261	-0.065
Initial FS density					1.000	0.851
FSLR						1.000

* 29 data points used to derive each r-value

Stepwise Multiple Regression--

The linear regression analyses discussed above provided insight in determining which factors were responsible for the variation observed in the data. Further refinement in quantifying these effects was possible by performing stepwise multiple regression analyses in which ordered, linear models were developed to predict the overall net effect of all variables on contactor performance.

The procedure involves re-examination, at every stage of the regression, of the variables incorporated into the model in previous stages. A variable which may have been the best single variable to enter at an early stage may, at a later stage, be superfluous because of the relationships between it and other variables not in the regression. A judgement on the contribution of each variable is made after each step of the analysis, as though it had been the most recent variable entered, irrespective of its actual point of entry into the model. Any variable which provides a nonsignificant contribution is removed from the model. This process is continued until no more variables will be admitted to the equation and no more are rejected. The final result is a multiple regression equation including all variables contributing to the effect under examination.

A total of six equations resulted from this analysis, three for the packed column and three for the jet scrubber. The dependent variables under examination were TCLR, FCLR, and FSLR. The independent variables were initial TC, FC, or FS density, ozone dosage, utilization, consumption, and residual. The three equations for the packed column are given as follows:

$$\text{Log } \frac{X_o}{X} = 0.61 \text{ Log } X_o + 0.34C_o - 1.77 \quad (r = 0.671) \qquad (15)$$

where X_o = initial total coliform density, X = total coliform density after ozonation, C_o = ozone consumption (mg/ℓ), and D_o = ozone dosage (mg/ℓ).

$$\text{Log } \frac{Y_o}{Y} = 0.82 \text{ Log } Y_o + 0.47U_o - 0.14D_o - 2.76 \quad (r = 0.698) \qquad (16)$$

where Y_o = initial fecal coliform density, Y = fecal coliform density after ozonation, and U_o = ozone utilization (mg/ℓ).

$$\text{Log } \frac{Z_o}{Z} = 0.78 \text{ Log } Z_o + 0.21U_o - 1.76 \quad (r = 0.958) \qquad (17)$$

where Z_o = initial fecal strep density and Z = fecal strep density after ozonation.

The multiple correlation coefficients (r) were significant at the $\alpha < 0.05$ level.

It is clear from these equations that initial bacterial density was an important contributing factor to the variation in the data. Thus, when predicting the effect of ozone on the microorganism reduction efficiency of a packed column, one must account for the initial bacterial numbers in the overall model.

It was previously shown that ozone utilization, consumption, and residual in the packed column were mathematically related to applied dosage (equations 11 to 13). If these relationships are substituted into equations 15 to 17 so that log microorganism reduction is expressed in terms of initial bacterial density and dosage alone, the latter equations simplify to:

$$TCLR = 0.04\ D_o + 0.6 \log X_o - 1.4 \quad (18)$$

$$FCLR = 0.06\ D_o + 0.8 \log Y_o - 2.0 \quad (19)$$

$$FSLR = 0.09\ D_o + 0.8 \log Z_o - 1.4 \quad (20)$$

Thus, if the initial total coliform density were 10^6/100 ml, the ozone dosage needed to achieve a 3 log reduction in the packed column would be 20 mg/ℓ.

The equations for the jet scrubber are given as follows:

$$TCLR = \text{Log} \frac{X_o}{X} = 0.39R_o + 0.99 \text{ Log } X_o - 4.01 \quad (r = 0.678) \quad (21)$$

$$FCLR = \text{Log} \frac{Y_o}{Y} = 0.68R_o + 1.07 \text{ Log } Y_o - 3.95 \quad (r = 0.747) \quad (22)$$

$$FSLR = \text{Log} \frac{Y_o}{Y} = 0.46R_o + 0.79 \text{ Log } Y_o - 1.55 \quad (r = 0.884) \quad (23)$$

The multiple r-values were significant at the $\alpha<0.05$ level.

It is clear that, aside from initial bacterial density, the only factor significantly affecting microorganism reduction efficiency in the jet scrubber was ozone residual. Substituting equation 14 into equations 21 to 23 so that microorganism reduction is given in terms of initial bacterial numbers and applied dosage, the relationships become:

$$TCLR = 0.03D + \log X_o - 4.0 \quad (24)$$

$$FCLR = 0.05D + 1.1 \log Y_o - 3.9 \quad (25)$$

$$FSLR = 0.03D + 0.8 \log Z_o - 1.5 \quad (26)$$

Thus, to achieve a 3 log reduction of total coliforms in the jet scrubber, assuming an initial density of 10^6/100 ml, the applied ozone dosage would be 33 mg/ℓ. This is considerably higher than in the packed column.

It should be pointed out that the above data were obtained at a constant ozone gas concentration of 10 mg/ℓ and varying gas flow rates. According to Henry's Law, mass transfer depends on the difference between the ozone concentration in the gas and in the liquid. Increasing the concentration of

ozone in the gas stream would enable operation of the contactors at lower gas flow rates and thus improve mass transfer efficiency. This would presumably improve microorganism reduction efficiency as well, since more ozone would be added to the liquid. Work is presently underway to verify this hypothesis experimentally.

PHASE 2 - PARALLEL OPERATIONAL MODE - FACTORIAL EXPERIMENT

During this phase of the investigation, both contactors were operated in parallel on effluent from the Robert A. Taft Laboratory pilot plant facility.

The experimental arrangement described in Section 4 enables the investigator to test the significant differences in performance between the two ozone contactors with minimum bias. Moreover, if the resulting analyses of variance (ANOVA) indicate significant interactions between the various levels of one factor and those of another, the data can be easily subjected to linear and stepwise multiple regression analyses to determine which physical-chemical characteristics of the effluent contribute to such interactions and to quantify the extent to which each parameter is involved.

Characteristics of the Wastewater Effluent

Table 17 summarizes the mean, standard deviation, and range of the physical-chemical characteristics of the filtered pilot plant effluent used in this phase of the study. Effluent was generally poorer than that of the MCWTP effluent (Table 2).

TABLE 17. CHARACTERISTICS OF THE PILOT PLANT EFFLUENT PRIOR TO OZONATION

Parameter	Mean* mg/ℓ	Standard deviation mg/ℓ	Range mg/ℓ
Temperature (C)	14	0.5	13 - 14
TCOD	76	20	41 - 106
SCOD	65	23	34 - 105
TOC	19.9	6.3	8.2 - 30.5
TSS	6	3	2 - 11
TURB (JTU)	11.3	12.4	1.6 - 40
TKN	16.1	7.9	6.5 - 27
NH_4-N	8.6	3.0	3.6 - 14.1
ORG-N	7.4	6.9	2.2 - 30.5

* 24 data points

Total Coliform Log Reduction (TCLR)

Table 18 illustrates the split-split plot layout as described in Section 4 and summarizes the data for log total coliform reduction in both contactors. Analysis of the data from Table 18 is shown in Table 19. Examination of the geometric mean total coliform densities (after ozonation) in Table 18 reveals

that a coliform reduction to a level less than 1000 TC/100 ml was achieved in the packed column only at a dosage of 19.5 mg/ℓ. Such a level of disinfection was not achieved in the jet scrubber.

If the computed F-statistic in Table 19 with the appropriate degrees of freedom is greater than the corresponding F-value from the F-distribution table (5 percent significance level), the effect under examination is significant. The various F-statistics were computed as follows: (1) Dose main effect (D_j) -- the Mean Square (MS) for doses was ratiod against the MS for the R_iD_j interaction; (2) Replication main effect (R_i) -- the MS for replication was ratiod against the MS for the R_iD_j interaction; (3) C_kD_j interaction effect -- the MS for the C_kD_j was ratiod against the MS for the $R_iD_jC_k$ interaction; (4) C_kR_i interaction effect -- the MS for the C_kR_i interaction was ratiod against the MS for the $R_iD_jC_k$ interaction. To test for a significant difference between the two contactors (contactor main effect), a Pseudo-F test was performed in which the mean square (MS) for contactors (C_k) was ratiod against the MS for the R_iC_k interaction plus the MS for the D_jC_k interaction minus the mean square for the $R_iD_jC_k$ interaction.

TABLE 18. SPLIT-SPLIT-PLOT LAYOUT FOR TOTAL COLIFORM LOG REDUCTION DATA

	Packed column, TCLR				Jet scrubber, TCLR			
	O_3 dose, mg/ℓ				O_3 dose, mg/ℓ			
Replicates	4.9	9.7	13.1	19.5	4.9	9.7	13.1	19.5
1	2.03	3.09	4.15	3.14	1.00	1.86	3.00	2.52
2	1.00	2.15	2.22	2.00	1.00	0.30	0.07	0.31
3	2.00	2.46	3.35	2.86	0.14	1.79	2.54	2.27
4	1.00	3.02	3.22	3.31	0.16	0.81	0.91	2.16
5	0.03	0.85	1.35	4.02	0.00	0.03	0.00	2.48
6	0.24	1.16	1.27	3.43	0.07	0.43	0.03	1.16
Mean	1.05	2.12	2.59	3.13	0.40	0.87	1.09	1.82
Standard deviation	0.84	0.94	1.17	0.67	0.47	0.78	1.35	0.89
Effluent geometric mean, TC/100 mℓ	9.9×10^4	8.7×10^3	2.2×10^3	5.5×10^2	4.7×10^5	1.6×10^5	8.9×10^4	1.6×10^4

TABLE 19. ANOVA OF TOTAL COLIFORM LOG REDUCTION DATA

Source of variation	Degrees of freedom	Sums of squares	Mean squares	F	F ($\alpha = 0.05$)
Contactors (C_k)	1	16.70	16.70	51.80	37.0
Doses (D_j)	3	19.14	6.38	7.90	3.29
Replicates (R_i)	5	17.92	3.58	4.45	2.90
C_kD_j	3	1.20	0.40	1.70	3.29
C_kR_i	5	0.79	0.16	0.67	2.90
R_iD_j	15	12.07	0.80		
$R_iD_jC_k$	15	3.54	0.24		
Total	47	71.36			

Results from Table 19 indicate that the difference between the two ozone contactors (C_k) with respect to TCLR was significant at the 5 percent significance level. It can also be seen that the dosage effect (D_j) on the combined TCLR in both contactors was significant at the 5 percent significance level. This is not unexpected, since an increase in ozone dosage should cause a corresponding increase in coliform reduction. Significant differences in TCLR for both contactors were observed among replicate experiments (R_i), indicating that effluent quality varied from day to day and that these variations affected coliform reduction efficiency in both contactors.

The interaction between contactor and dosage ($C_k D_j$) was not significant (Table 19). This means that the difference between the two contactors with respect to TCLR was consistent at all dosage levels studied. The interaction between contactors and replication ($C_k R_i$) was also not significant. This indicates that the differences in TCLR observed between the two contactors were the same regardless of effluent quality.

The relationship between TCLR and applied ozone dose in each contactor is depicted graphically in Figure 15. Each point is the mean of the six replicate experiments. It can be seen that TCLR was better in the packed column than in the jet scrubber (significant contactor main effect) and that TCLR was directly proportional to dosage (significant dosage main effect). The fact that the two lines are nearly parallel illustrates the lack of a significant contactor-dosage ($C_k D_j$) interaction. The replication main effect (i.e. effect of effluent quality) is illustrated in Figure 16, where the average TCLR in each contactor at all dosage levels is plotted against total chemical oxygen demand in the pilot plant effluent. Each point is the mean TCLR at the four dosage levels. It is evident that an increase in TCOD (a variable representative of effluent quality) corresponded to a decrease in TCLR in both contactors. Moreover, the lack of a significant contactor-replication interaction ($C_k R_i$) is evidenced by the parallel nature of the two lines. Thus, effluent quality adversely affected overall TCLR efficiency in both contactors. The packed column significantly and consistently outperformed the jet scrubber with respect to total coliform reduction at all dosage levels studied and under varying conditions of effluent quality.

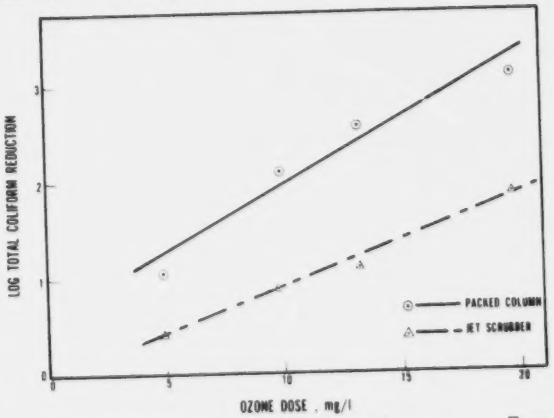


Figure 15. Total Coliform Log Reduction as a Function of Ozone Dosage in the Packed Column and Jet Scrubber

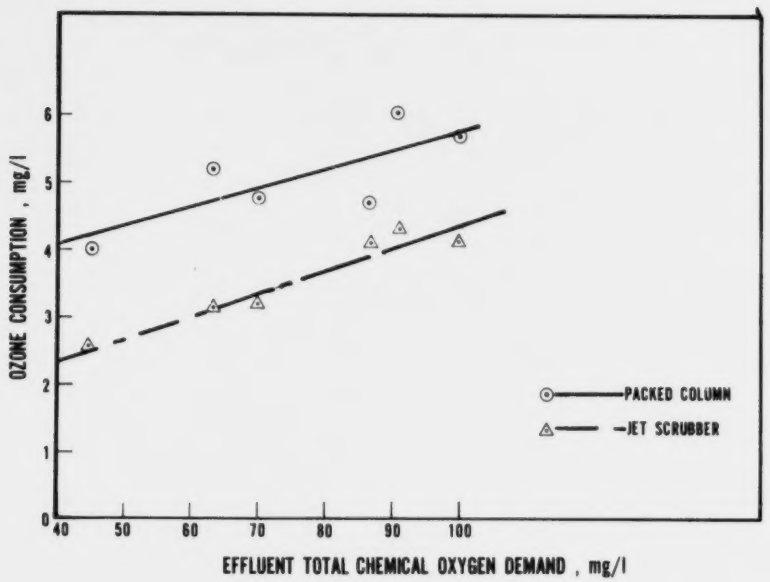


Figure 16. Total Coliform Log Reduction at all Dosage Levels as a Function of Effluent Total Chemical Oxygen Demand in the Packed Column and Jet Scrubber

Fecal Coliform Log Reduction (FCLR)

Table 20 summarizes the data for log fecal coliform reduction in both contactors. Analysis of the data from Table 20 is presented in Table 21.

Results from Table 21 are similar to those depicted in Table 19. All main effects were significant, and both interactions were not significant. Thus, as with total coliform reduction, the packed column outperformed the jet scrubber with respect to fecal coliform reduction at all dosage levels studied and at all conditions of effluent quality.

Examination of the geometric mean fecal coliform densities (after ozonation) in Table 20 reveals that a mean FC reduction to a level of less than 200/100 ml was almost achieved in the peaked column at the highest dosage level but not even approached in the jet scrubber. These results are comparable to the total coliform data.

TABLE 20. SPLIT-SPLIT-PLOT LAYOUT FOR FECAL COLIFORM LOG REDUCTION DATA

	Packed column FCLR				Jet scrubber FCLR			
	Dose, mg/ℓ				Dose, Mg/ℓ			
Replicates	4.9	9.9	13.1	19.5	4.9	9.7	13.1	19.5
1	2.35	3.15	3.33	3.21	1.07	2.06	2.54	2.60
2	0.49	2.17	1.27	2.71	0.50	0.84	0.14	0.00
3	1.29	3.00	1.52	3.00	0.29	2.81	1.87	2.00
4	0.15	2.95	3.93	3.02	0.15	1.15	1.35	1.43
5	0.0	0.31	2.65	3.33	0.18	0.0	0.0	2.17
6	0.31	0.66	3.15	3.52	0.14	0.14	0.0	0.66
Mean	0.76	2.04	2.64	3.13	0.39	1.17	0.98	1.48
S.D.	0.90	1.26	1.05	0.28	0.36	1.10	1.09	0.99
Effluent geometric mean, FC/100 ml	4.6×10^4	3.6×10^3	5.7×10^2	2.2×10^2	1.2×10^5	2.9×10^4	3.7×10^4	7.3×10^3

TABLE 21. ANOVA FOR FECAL COLIFORM LOG REDUCTION DATA

Source of variation	Degrees of freedom	Sums of squares	Mean squares	F	F (α=0.05)
Contactors (C_j)	1	15.62	15.62	13.93	13.50
Doses (D_j)	3	19.03	6.34	8.46	3.29
Reps (R_i)	5	15.48	3.10	4.13	2.90
$C_k D_j$	3	3.56	1.19	2.64	3.29
$C_k R_i$	5	1.92	0.38	0.85	2.90
$R_i D_j$	15	11.25	0.75		
$R_i D_j C_k$	15	6.75	0.45		
Total	47	73.60			

Percent Ozone Utilization

Table 22 illustrates the split-split-plot layout and summarizes the data for percent ozone utilization as a function of ozone dosage. Analysis of the data from Table 22 is given in Table 23.

Results indicate that the difference between the two ozone contactors (C_k) with respect to percent ozone utilization was significant. In addition, percent ozone utilization in both contactors was significantly different at all dosage levels studied (D_j). Replication (R_i) did not significantly affect percent ozone utilization in either contactor. Thus, variation in effluent quality did not bring about a corresponding variation in percent ozone utilization at the four dosage levels studied.

Neither the contactor-dosage (C_kD_j) interaction nor the contactor-replication (C_kR_i) interaction with respect to percent ozone utilization were significant in this experiment. This means that the differences observed between the contactors were consistent at all dosage levels studied and at all conditions of effluent quality experienced.

The relationship between percent ozone utilization and applied ozone dose in each contactor is depicted graphically in Figure 17. Each point is the mean of six replicate experiments. It can be seen that percent ozone utilization was better in the packed column than in the jet scrubber (significant contactor main effect) and that percent ozone utilization was inversely proportional to dosage (significant dosage main effect). The fact that the lines are parallel illustrates the lack of significant contactor-dosage (C_kD_j) interaction. The lack of a significant replication main effect (i.e., effect of effluent quality) is illustrated in Figure 18 where the average percent ozone utilization in each contactor at all dosage levels is plotted against TCOD in the influent wastewater. Each point is the mean percent ozone utilization at the four dosage levels. It is evident that an increase in TCOD was not accompanied by any significant overall change in percent ozone utilization in both contactors. In addition, the lack of a significant contactor-replication interaction (C_kR_i) is evidenced by the nearly parallel nature of the two lines. The packed column significantly and consistently outperformed the jet scrubber with respect to percent ozone utilization at all dosage levels studied and under varying conditions of effluent quality. However, effluent quality did not significantly affect overall percent utilization in either contactor.

Actual Ozone Utilization

Table 24 illustrates the split-split-plot layout and summarizes the data for ozone utilization. Analysis of the data from Table 24 is given in Table 25.

Results indicate that the difference between the two ozone contactors (C_k) with respect to ozone utilization was significant. In addition, ozone utilization in both contactors combined was significantly different at each dosage level (D_j) studied. The replication main effect (R_i) was not significant. This means that overall ozone utilization in both contactors was not

TABLE 22. SPLIT-SPLIT - PLOT LAYOUT FOR PERCENT OZONE UTILIZATION DATA

	Packed column, ozone utilized, percent				Jet scrubber ozone utilized, percent			
	Dose mg/ℓ				Dose mg/ℓ			
Replicates	4.9	9.7	13.1	19.5	4.9	9.7	13.1	19.5
1	78	57	42	34	45	32	23	20
2	67	49	49	49	57	32	32	37
3	78	52	46	40	52	26	25	25
4	73	56	43	35	53	34	27	21
5	61	58	49	43	61	41	32	27
6	68	63	53	43	65	43	35	27
Mean	71	56	47	41	56	35	29	27
S.D.	6.7	4.9	4.1	5.6	7.1	6.3	4.7	6.1

TABLE 23. ANOVA FOR PERCENT OZONE UTILIZATION DATA

Source of variation	Degrees of freedom	Sums of squares	Mean squares	F	F (α=0.05)
Contactors (C_k)	1	3570.75	3570.75	77.81	7.60
Doses (D_j)	3	6159.08	2053.03	65.92	3.29
Reps (R_i)	5	384.67	76.93	2.47	2.90
C_kD_j	3	81.42	27.14	1.40	3.29
C_kR_i	5	191.00	38.20	1.96	2.90
R_iD_j	15	467.17	31.14		
$R_iD_jC_k$	15	291.76	19.45		
Total	47	11,145.84			

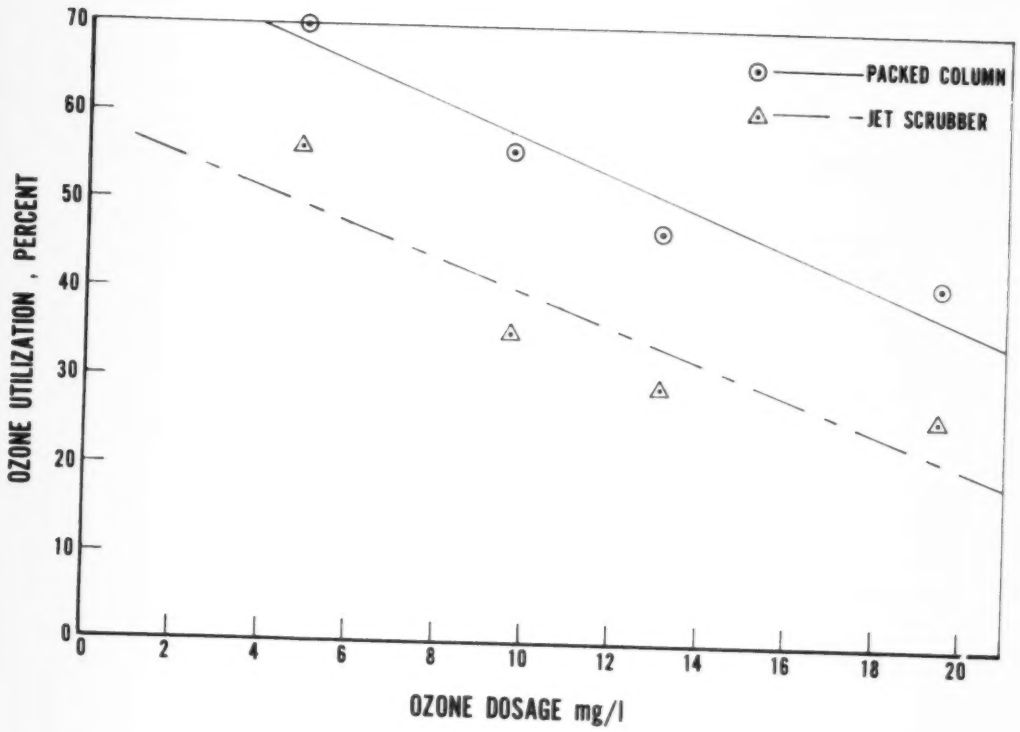


Figure 17. Percent Ozone Utilization as a Function of Ozone Dosage in the Packed Column and Jet Scrubber

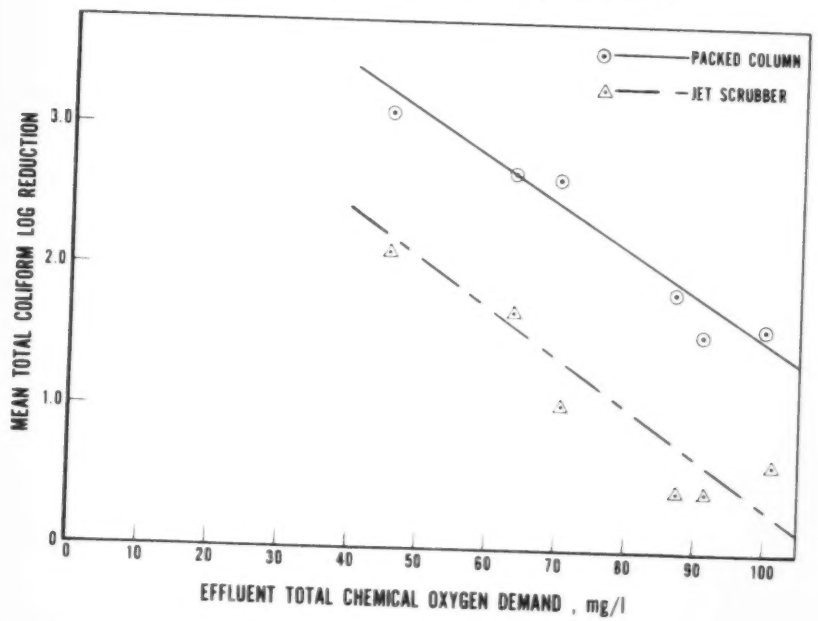


Figure 18. Percent Ozone Utilization as a Function of Effluent Total Chemical Oxygen Demand in the Packed Column and Jet Scrubber

TABLE 24. SPLIT-SPLIT-PLOT LAYOUT FOR OZONE UTILIZATION DATA

	Packed column ozone utilized, mg/ℓ				Jet scrubber ozone utilized, mg/ℓ			
	dose mg/ℓ				dose mg/ℓ			
Replicates	4.9	9.7	13.1	19.5	4.9	9.7	13.1	19.5
1	3.8	5.5	5.5	6.6	2.2	3.1	3.0	3.9
2	3.2	4.8	6.4	9.6	2.7	3.1	4.2	7.2
3	3.7	5.0	5.9	7.8	2.5	2.5	3.2	4.8
4	3.5	5.5	5.7	6.9	2.5	3.3	3.6	4.2
5	2.9	5.6	6.5	8.4	2.9	3.9	4.2	5.3
6	3.3	6.1	6.9	8.4	3.1	4.2	4.6	5.3
Mean	3.4	5.4	6.2	8.0	2.7	3.4	3.8	5.1
S.D.	0.3	0.5	0.6	1.1	0.3	0.6	0.6	1.2

TABLE 25. ANOVA FOR OZONE UTILIZATION DATA

Source of variation	Degrees of freedom	Sums of squares	Mean squares	F	F (α=0.05)
Contactors (C_k)	1	47.9	47.9	19.0	9.1
Doses (D_j)	3	75.7	25.2	33.8	3.3
Reps (R_i)	5	7.8	1.6	2.1	2.9
$C_k D_j$	3	7.3	2.4	38.9	3.3
$C_k R_i$	5	0.8	0.2	2.5	2.9
$R_i D_j$	15	11.2	0.7		
$R_i D_j C_k$	15	0.9	0.1		
Total	47	151.5			

significantly affected by changes in effluent quality.

The contactor-dosage (C_kD_j) interaction with respect to ozone utilization was significant at the 5 percent level (Table 25). This contrasts with the lack of interaction between contactor and dosage with respect to log total and fecal coliform reduction(Tables 19 and 21) and percent ozone utilization (Table 23). This means that the difference in actual ozone utilization between the packed column and the jet scrubber at some dosage levels was not the same at other dosage levels.

Finally, the contactor-replication (C_kR_i) interaction with respect to ozone utilization was not significant. This means that the difference in performance of the two contactors with respect to ozone utilized was the same regardless of effluent quality. This effect was also observed for log total and fecal coliform reduction and percent ozone utilization.

These effects are clearly visualized by examining Figures 19 and 20. The relationship between ozone utilization and applied ozone dose in each contactor is depicted graphically in Figure 19. Each point is the mean of six replicate experiments. It can be seen that ozone utilization in the packed column was better than in the jet scrubber (significant contactor main effect) and that ozone utilization in both contactors was proportional to dosage (significant dosage main effect). The fact that the two lines are not parallel illustrates the significant contactor-dosage interaction (C_kD_j). As dosage increased, the increase in ozone utilization in the packed column was greater than in the jet scrubber. The lack of a significant replication main effect is illustrated in Figure 20, where the average ozone utilization in each contactor at all dosage levels is plotted against TCOD in the pilot plant effluent. Each point is the mean ozone utilization at the four dosage levels. It is evident that an increase in TCOD was not accompanied by any significant overall change in ozone utilization in either contactor. Moreover, the lack of significant contactor-replication interaction (C_kR_i) is evidenced by the nearly parallel nature of the two lines. Thus, the packed column significantly outperformed the jet scrubber with respect to actual utilization. Effluent quality did not significantly affect overall ozone utilization in both contactors; however, it will be seen later that ozone utilization in each contactor was affected by effluent quality at certain individual dosage levels.

Ozone Residual

Table 26 illustrate the split-split-plot layout and summarizes the data for ozone residual. Analysis of the data from Table 26 is given in Table 27.

Results indicate that the difference between the two ozone contactors (C_k) with respect to ozone residual was significant at the 5 percent level. In addition, ozone residual was significantly different at each dosage level (D_j) studied. This is expected, since ozone residual should increase with increasing dosage. Finally, Table 27 indicates that effluent quality (replication) significantly affected the magnitude of ozone residual in the effluent from both contactors. Thus, as effluent quality deteriorated, ozone residual decreased at the same applied dosage level.

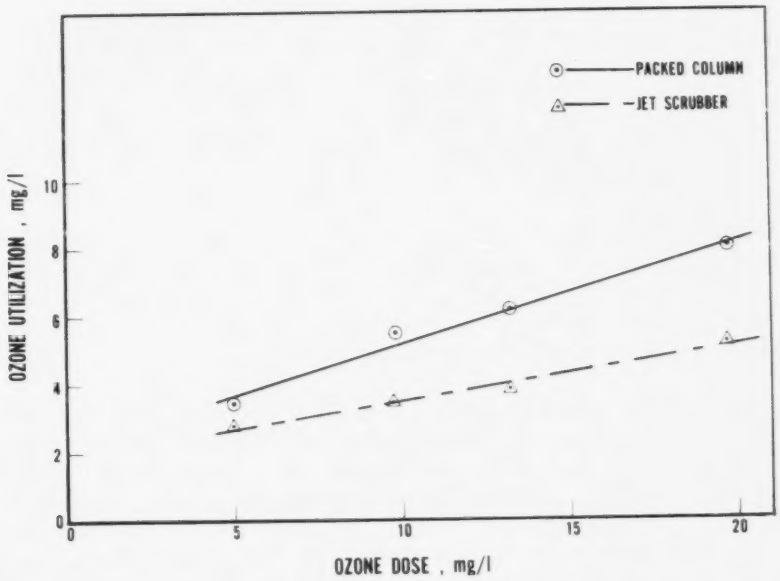


Figure 19. Ozone Utilization as a Function of Ozone Dosage in the Packed Column and Jet Scrubber

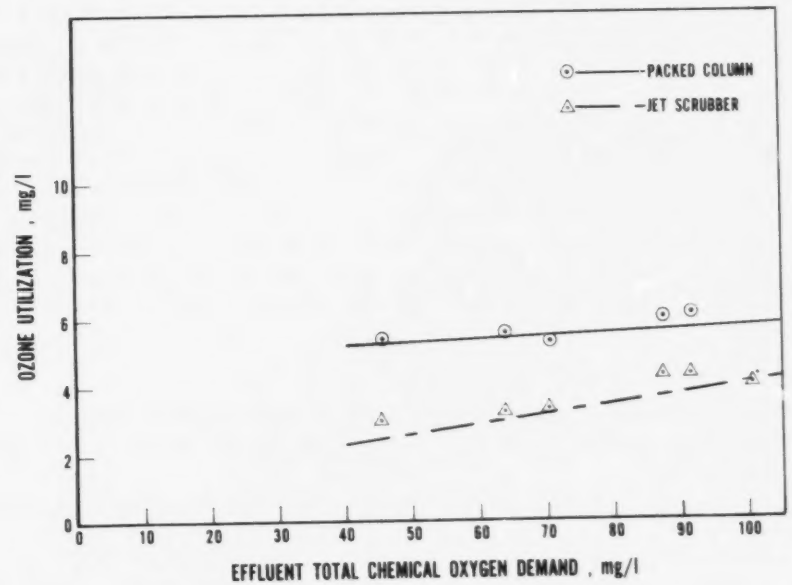


Figure 20. Ozone Utilization at all Dosage Levels as a Function of Effluent Total Chemical Oxygen Demand in the Packed Column and Jet Scrubber

TABLE 26. SPLIT-SPLIT-PLOT LAYOUT
FOR OZONE RESIDUAL DATA

	Packed column ozone residual, mg/ℓ dose, mg/ℓ				Jet scrubber ozone residual, mg/ℓ dose, mg/ℓ			
Replicates	4.9	9.7	13.1	19.5	4.9	9.7	13.1	19.5
1	0.9	0.9	1.7	1.9	0.2	0.3	0.8	0.7
2	0.1	0.3	0.4	0.9	0.0	0.2	0.2	0.2
3	0.6	1.4	1.6	1.6	0.1	0.4	0.5	0.4
4	0.2	0.4	1.1	0.9	0.0	0.2	0.3	0.4
5	0.0	0.2	0.4	0.2	0.0	0.0	0.0	0.0
6	0.0	0.1	0.2	0.4	0.0	0.0	0.1	0.0
Mean	0.3	0.6	0.9	1.0	0.05	0.2	0.3	0.3
S.D.	0.4	0.5	0.7	0.7	0.08	0.2	0.3	0.3

TABLE 27. ANOVA FOR OZONE RESIDUAL DATA

Source of variation	Degrees of freedom	Sums of squares	Mean squares	F	F (α=0.05)
Contactors (C_K)	1	2.71	2.71	7.80	5.60
Doses (D_j)	3	1.69	0.56	11.24	3.29
Reps (R_i)	5	5.10	1.02	20.32	2.90
C_kD_j	3	0.37	0.12	8.98	3.29
C_kR_i	5	1.18	0.24	16.99	2.90
R_iD_j	15	0.75	0.05		
$R_iD_jC_k$	15	0.21	0.01		
Total	47	12.02			

The contactor-dosage (C_kD_i) interaction with respect to ozone residual was also significant. This means that the difference in ozone residual between the contactors was not consistent with effluent quality.

The relationship between ozone residual and applied ozone dosage in each contactor is depicted graphically in Figure 21. Each point is the mean of six replicate experiments. It can be seen that ozone residual in the packed column was higher than in the jet scrubber (significant contactor main effect) and that ozone residual in both contactors was proportional to dosage (significant dosage main effect). The fact that the two lines are not parallel illustrates the significant contactor-dosage interaction (C_kD_i). As dosage increased, the increase in ozone residual in the packed column was greater than in the jet scrubber. The significant replication main effect is illustrated in Figure 22, where average ozone residual in each contactor at all dosage levels is plotted against TCOD of the effluent. Each point is the mean ozone residual at the four dosage levels. It is evident that an increase in TCOD corresponds to a decrease in ozone residual in both contactors. Moreover, the significant contactor-replication interaction(C_kR_i) is evidenced by the fact that the two lines intersect. Thus, the magnitude of the ozone residual in the packed column appeared to be more sensitive to changes in applied ozone dosage (Figure 21) and shift in ozone demand (Figure 22) than in the jet scrubber. This is most likely because the packed column was a better overall ozone contactor than the jet scrubber.

Ozone Consumption

Table 28 illustrates the split-split-plot layout and summarizes the data for ozone consumption (i.e., the difference between actual ozone utilization and ozone residual). Analysis of the data from Table 28 is given in Table 29.

Results indicate that all main effects were significant and both interactions were significant. This is similar to the ozone residual data analysis presented in Table 27. Thus, consumption in both contactors was significantly different; dosage and wastewater quality significantly affected consumption in both contactors; and the significant differences in consumption between the contactors were not consistent over all levels of dosage and under different conditions of wastewater quality.

The relationship between ozone consumption and applied ozone dose in each contactor is depicted graphically in Figure 23. Each point is the mean of six replicate experiments. It can be seen that more ozone was consumed in the packed column than in the jet scrubber (significant contactor main effect) and that ozone consumption was proportional to dosage (significant dosage main effect). The fact that the two lines intersect illustrates the significant contactor-dosage interaction (C_kD_i). The replication main effect is illustrated in Figure 24, where the average ozone consumption in each contactor at all dosage levels is plotted against total chemical oxygen demand in the pilot plant effluent. Each point is the mean ozone consumption at the four dosage levels. It is evident that an increase in TCOD corresponded to an increase in ozone consumed in both contactor. However, the TCOD effect on ozone consumption in both contactors, although statistically significant, was for all practical purposes negligible, as a 60 mg/ℓ increase in TCOD

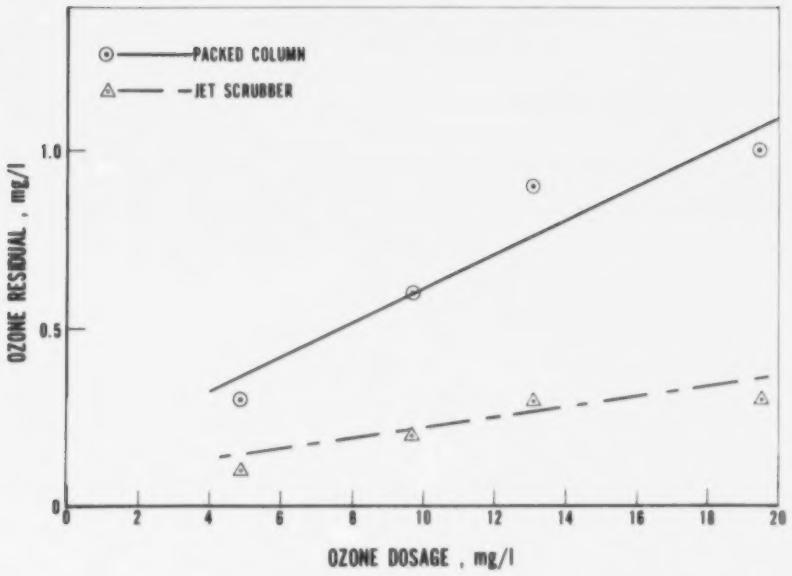


Figure 21. Ozone Residual as a Function of Ozone Dosage in the Packed Column and Jet Scrubber

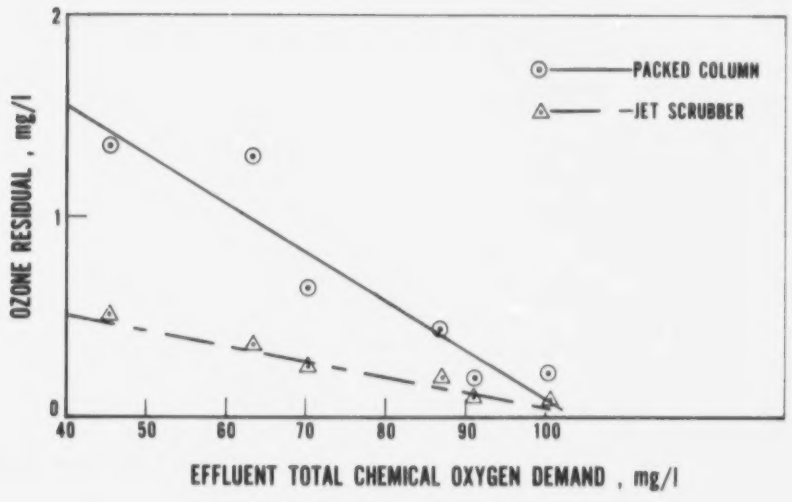


Figure 22. Ozone Residual as a Function of Effluent Total Chemical Oxygen Demand in the Packed Column and Jet Scrubber

TABLE 28. SPLIT-SPLIT-PLOT LAYOUT FOR OZONE CONSUMPTION DATA

	Packed column ozone consumption, mg/ℓ				Jet scrubber ozone consumption, mg/ℓ			
	dose, mg/ℓ				dose, mg/ℓ			
Replicates	4.9	9.7	13.1	19.5	4.9	9.7	13.1	19.5
1	2.9	4.6	3.8	4.7	2.0	2.8	2.2	3.2
2	2.6	3.4	4.8	8.0	2.6	3.1	3.7	6.8
3	3.6	4.7	5.5	6.9	2.5	2.3	3.0	4.6
4	3.3	5.1	4.6	6.0	2.5	3.1	3.3	3.8
5	2.9	5.4	6.1	8.2	2.9	3.9	4.2	5.3
6	3.3	6.0	6.7	8.0	3.1	4.2	4.5	5.3
Mean	3.1	4.9	5.3	7.0	2.6	3.2	3.5	4.8
S.D.	0.4	0.9	1.1	1.4	0.4	0.7	0.8	1.3

TABLE 29. ANOVA FOR OZONE CONSUMPTION DATA

Source of variation	Degrees of freedom	Sums of squares	Mean squares	F	F (α=0.05)
Contactors (C_k)	1	27.26	27.26	14.60	7.71
Doses (D_j)	3	56.44	18.81	20.87	3.29
Reps (R_i)	5	17.87	3.57	3.96	2.90
C_kD_j	3	4.56	1.52	14.20	3:29
C_kR_i	5	2.28	0.46	4.26	2.90
R_iD_j	15	13.52	0.90		
$R_iD_jC_k$	15	1.60	0.11		
Total	47	123.53			

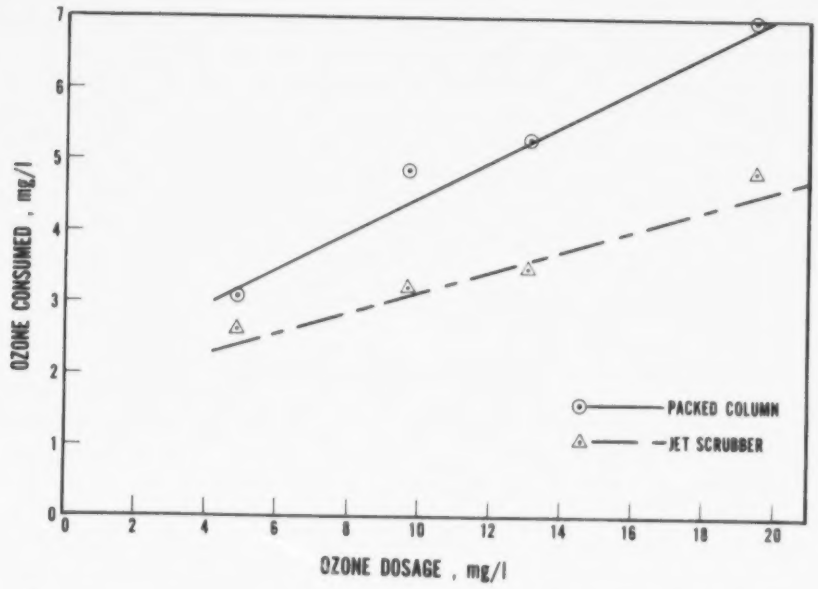


Figure 23. Ozone Consumption as a Function of Ozone Dosage in the Packed Column and Jet Scrubber

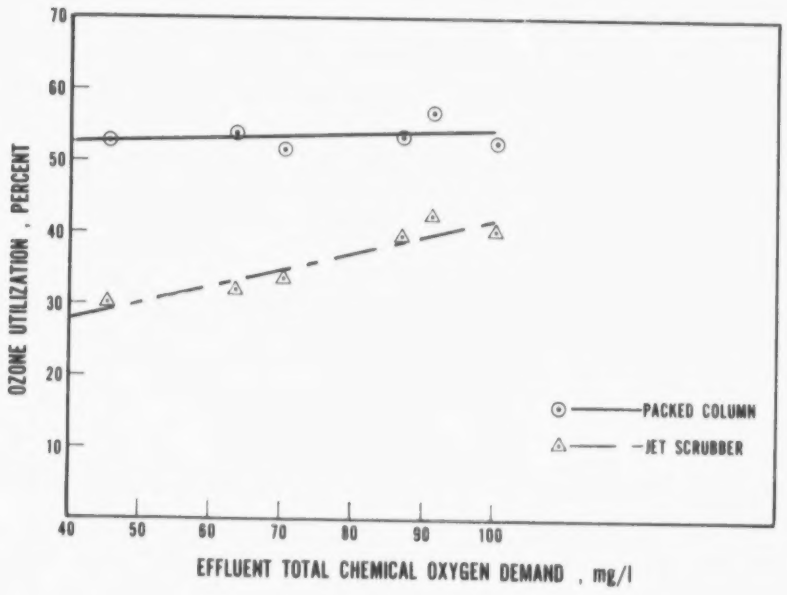


Figure 24. Ozone Consumption as a Function of Effluent Total Chemical Oxygen Demand in the Packed Column and Jet Scrubber

corresponded to less than 2 mg/ℓ increase in ozone consumption. The daily variation of the difference in ozone comsumption between contactors (contactor-replication interaction) was also satistically significant. Hence, the two lines in Figure 24, although appearing parallel, have significantly different slopes, but from a practical standpoint the difference is considered negligible. Thus, it appears that ozone consumption in both contactors was more dependent on applied ozone dosage (Figure 23) than on the demand of the effluent being treated (Figure 24). More ozone was consumed in the packed column than in the jet scrubber, and the increase in consumption as a function of dosage was greater in the packed column.

Summary of the Factorial Experiment--

On the basis of total and fecal coliform log reduction, it is clear that the packed column contactor was superior to the jet scrubber, at least within the limits of effluent quality encountered and ozone dosages used (5 - 20 mg/ℓ). Effluent quality significantly affected microorganism reduction efficiency in both contactors.

On the basis of ozone utilization efficiency, several conclusions can be made. First, the packed column was superior to the jet scrubber with respect to percent ozone utilization, regardless of effluent quality and the magnitude of applied dosage. This superiority was significant and consistent at all dosage levels employed. Percent utilization in both contactors was inversely proportional to dosage. Since dosage was increased by maintaining the ozone concentration in the gas stream constant and varying the gas flow rate, this result is not unexpected. Second, the packed column was superior to the jet scrubber with respect to actual ozone utilization regardless of effluent quality. The magnitude of this difference in performance actually increased with increasing dosage (significant $C_k D_j$ interaction). Ozone utilization in both contactors increased with increasing dosage, as expected. Third, both ozone residual and ozone consumption in each contactor increased with increasing dosage. Effluent quality had a greater effect on the magnitude of ozone residual in both contactors than on the amount of ozone consumed. Thus, since TCLR, FCLR, and ozone residual were significantly affected by effluent quality while overall ozone utilization and ozone consumption were less significantly affected, it follows that organism reduction was not mass transfer limited, but overall ozone utilization and consumption were. However, it should be emphasized that these were overall effects and no account has yet been made of the effect of effluent quality at each individual dosage level. This will be discussed in the following section.

Linear Regression Analysis of Data from the Factorial Experiment

The foregoing analyses of variance (ANOVA) were useful in enabling conclusions on the overall comparative disinfection and mass transfer efficiencies of the packed column and jet scrubber contactors. However, the ANOVA's do not reveal which factors in the effluent contributed to the variation in the data. Information of this kind would provide invaluable

assistance in designing or upgrading ozone contactors.

The factorial arrangement used in this study facilitates performance of other statistical tests to furnish the desired information, because both contactors were treated in parallel under identical conditions at four separate and distinct applied dosage levels. Thus, if it is desired to test the effect of chemical oxygen demand, for example, on coliform reduction in each contactor, there exists six data points at each dosage level to establish a correlation. Tests performed were linear regression analysis.

Total Coliform Reduction - Packed Column--

Table 30 summarizes the correlation between total coliform log reduction (TCLR) in the packed column and each effluent quality variable at different applied ozone dosage levels.

A correlation coefficient greater than 0.73 or less than -0.73 in Table 30 is significantly different from zero at the 95 percent confidence level.

It is clear from Table 30 that chemical oxygen demand (total and soluble) and total organic carbon significantly interfered with TCLR in the packed column at dosage levels ranging from 4.9 to 13.1 mg/ℓ. At 19.5 mg/ℓ ozone dosage, TKN and organic-N significantly interfered with TCLR, but not TCOD, SCOD, or TOC. Thus, at all dosage levels TCLR appears to have been rate limited since the magnitude of TC reduction was affected by the effluent quality.

It appears that a strong negative correlation was associated with total suspended solids and TCLR at 4.9 mg/ℓ ozone dosage but not at the higher dosages. Although it is possible that TSS exerted an ozone demand at low applied ozone levels, it is likely that this observation was an experimental artifact, because the variation in TSS from day-to-day was not high enough to warrant such a conclusion. Data on unfiltered effluent are needed to better quantify this relationshiip.

It appears that a strong positive correlation existed between ammonium-N and TCLR at 4.9, 9.7, and 13.1 mg/ℓ applied ozone but not at 19.5 mg/ℓ. This compares with the substantial negative correlation observed for TCOD, SCOD, and TOC at the same dosage levels and the lack of correlation at 19.5 mg/ℓ applied ozone. Since NH_4^+-N was inversely related to TCOD, SCOD, and TOC in this effluent (Table 17), it is likely that the above observation merely reflects the effect of COD and TOC on TCLR.

Total Kjeldahl nitrogen and organic nitrogen did not appear to affect disinfection efficiency until 19.5 mg/ℓ ozone was applied. This suggests that the organic demand exerted by COD and TOC in this effluent significantly affected TCLR in the packed column at lower ozone dosages but the demand exerted by nitrogenous compounds became significant at higher dosages. This conclusion would not be inconsistent with the observation that TKN and ORG-N did not correlate with COD or TOC.

TABLE 30. CORRELATION OF TOTAL COLIFORM LOG REDUCTION (TCLR) IN THE PACKED COLUMN AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	TCLR Correlation Coefficient (r)* Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	-0.96	-0.84	-0.98	0.22
SCOD	-0.96	-0.91	-0.97	0.14
TOC	-0.90	-0.68	-0.94	0.18
TSS	-0.83	0.10	-0.29	0.64
TKN	0.76	0.44	0.16	-0.88
TURB	-0.10	0.03	-0.11	-0.71
NH_4-N	0.87	0.72	0.82	-0.25
ORG-N	0.38	0.13	-0.08	-0.88

* 6 data points used to derive each r-value

Fecal Coliform Reduction - Packed Column--

Table 31 summarizes the correlation between fecal coliform log reduction (FCLR) in the packed column and each effluent quality variable at different applied ozone dosage levels.

Results from the FCLR data are similar to the TCLR data at 4.9 and 9.7 mg/ℓ applied ozone dosage. However, at 13.1 mg/ℓ, COD and TOC no longer affected FCLR, while TKN and ORG-N significantly interfered with FCLR. At 19.5 mg/ℓ ozone, the only variable adversely affecting FCLR was TCOD. No explanation can be offered for the latter observation except to suggest the observation may be artifactual. The demand exerted by nitrogenous material with respect to FCLR in the packed column became significant between 9.7 and 13.1 mg/ℓ applied ozone, while the same demand with respect to TCLR became significant at dosages greater than 13.1 mg/ℓ.

Total Coliform Reduction - Jet Scrubber--

Table 32 summarizes the correlation between total coliform log reduction (TCLR) in the jet scrubber and each effluent quality variable at different applied ozone dosage levels.

Results from Table 32 indicate that TCLR in the jet scrubber was not affected by any of the measured effluent parameters at 4.9 mg/ℓ applied ozone. The reason for this is that little microorganism reduction occurred at this dosage level (Table 18) to permit correlations to occur.

At 9.7 and 13.1 mg/ℓ, the same trend in TCLR noted in the packed column was observed in the jet scrubber. Thus, TCOD, SCOD, and TOC adversely affected TCLR, while NH_4^+-N showed a positive correlation. At 19.5 mg/ℓ ozone, the adverse affect of COD and TOC disappeared, but, in contrast to the packed column, TKN and ORG-N did not correlate with TCLR. Hence, TCLR in the jet scrubber was reaction rate limited at lower dosage levels but became mass transfer limited at a dosage somewhere between 13.1 and 19.5 mg/ℓ.

Fecal Coliform Reduction - Jet Scrubber--

Table 33 summarizes the correlation between fecal coliform log reduction (FCLR) in the jet scrubber and each effluent quality variable at different applied ozone dosage levels.

Results from Table 33 are similar to those in Table 32. The only difference is the significant negative correlation of FCLR with TOC at 4.9 mg/ℓ ozone. Thus, in general, FCLR was affected by the same parameters as TCLR in the jet scrubber.

Ozone Utilization - Packed Column--

Table 34 summarizes the correlation between ozone utilization in the packed column and each effluent quality variable at different applied ozone dosage levels.

TABLE 31. CORRELATION OF FECAL COLIFORM LOG REDUCTION (FCLR) IN THE PACKED COLUMN AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	FCLR Correlation Coefficient (r)* Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	-0.87	-0.84	-0.25	-0.77
SCOD	-0.82	-0.92	-0.29	-0.41
TOC	-0.91	-0.72	0.08	-0.64
TSS	-0.86	-0.07	0.63	-0.72
TKN	0.44	0.61	-0.82	0.21
TURB	-0.27	0.03	-0.40	0.07
NH_4-N	0.66	0.80	-0.28	0.56
ORG-N	0.09	0.28	-0.84	-0.02

* 6 data points used to derive each r-value

TABLE 32. CORRELATION OF TOTAL COLIFORM LOG REDUCTION (TCLR) IN THE JET SCRUBBER AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	TCLR Correlation Coefficients (r)* Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	-0.40	-0.94	-0.94	-0.39
SCOD	-0.36	-0.93	-0.92	-0.51
TOC	-0.67	-0.86	-0.87	-0.55
TSS	-0.74	0.12	-0.40	0.19
TKN	0.38	0.41	0.06	-0.40
TURB	0.57	-0.46	-0.44	-0.70
NH_4-N	0.27	0.88	0.82	0.39
ORG-N	0.32	0.02	-0.20	-0.64

* 6 data points used to derive each r-value

TABLE 33. CORRELATION OF FECAL COLIFORM LOG REDUCTION (FCLR) IN THE JET SCRUBBER AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	FCLR Correlation Coefficient (r)*			
	Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	-0.64	-0.83	-0.99	-0.48
SCOD	-0.60	-0.88	-0.99	-0.51
TOC	-0.83	-0.78	-0.90	-0.64
TSS	-0.78	-0.19	-0.26	-0.02
TKN	0.24	0.68	-0.01	-0.30
TURB	0.07	-0.25	-0.37	-0.69
NH_4-N	0.38	0.90	0.80	-0.47
ORG-N	0.04	0.32	-0.26	-0.57

* 6 data points used to derive each r-value

TABLE 34. CORRELATION OF OZONE UTILIZATION IN THE PACKED COLUMN AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	Ozone Utilization Correlation Coefficients (r)*			
	Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	-0.96	0.18	0.93	0.77
SCOD	-0.96	0.23	0.94	0.80
TOC	-0.69	0.30	0.93	0.71
TSS	-0.69	0.78	0.24	0.03
TKN	0.58	-0.89	-0.01	0.25
TURB	-0.32	-0.59	0.13	0.47
NH_4-N	0.96	-0.26	-0.67	-0.67
ORG-N	0.05	-0.90	0.20	0.60

* 6 data points used to derive each value

At an ozone dosage of 4.9 mg/ℓ there appears to be a significant negative correlation between ozone utilization and COD (total and soluble), while at 9.7 mg/ℓ no correlation exists, and at higher levels there is a positive correlation. This observation can be explained as follows. According to the International Critical Tables (16), the magnitude of Henry's Constant (H) increases as the temperature of the liquid increases. The mean temperature of the effluent in the six replicate experiments was 14 ^{o}C. At that temperature and an ozone concentration in the gas of 9.7 mg/ℓ the highest possible concentration of ozone which can exist in the liquid, regardless of the gas/liquid flow ratio, is 4.8 mg/ℓ. Thus, when the dosage is 4.9 mg/ℓ, (gas/liquid ratio = 0.5), it is theoretically possible for the liquid itself in the contactor to absorb 4.8 mg/ℓ regardless of the organic demand of the liquid. The driving force at any point in the column for mass transfer of ozone from the gas phase to the liquid phase is determined primarily by the difference in concentration of ozone in the gas stream and dissolved ozone. This difference in concentration diminishes as the gas rises through the column. At low dosage levels, most of the driving force occurs at the bottom of the column, and ozone will be absorbed into the water with or without the presence of organic demand. Therefore, it is reasonable to conclude that the significant negative correlation between ozone utilization and COD observed at 4.9 mg/ℓ dosage was coincidental.

At 9.7 mg/ℓ dosage (gas/liquid ratio = 1), the exhaust gas concentration was higher, and consequently a greater mass transfer driving force was available at the top of the column. This means not only that ozone absorption occurred more evenly through the length of the column but also that more ozone was available to react with organic demand. An average of 5.4 mg/ℓ ozone was utilized at that dosage, or 0.6 mg/ℓ more than the theoretical maximum allowable concentration. Since only 0.6 mg/ℓ of the 5.4 mg/ℓ ozone utilized can be attributed to the organic demand, no correlation was found between TCOD or SCOD and ozone utilization at 9.7 mg/ℓ dosage.

At dosage levels greater than 9.7 mg/ℓ, the dosage was sufficiently above the ozone solubility at that temperature and the driving force at the top of the column was sufficiently high relative to the TCOD and SCOD concentration that a change in TCOD and SCOD caused a corresponding change in ozone utilization. Hence, at 13.1 mg/ℓ applied ozone, an average of 6.2 mg/ℓ was utilized (1.4 mg/ℓ greater than the theoretical maximum), while at 19.5 mg/ℓ applied ozone, an average of 8.0 mg/ℓ was utilized (3.2 mg/ℓ greater than the theoretical maximum). This explains the high positive correlation between ozone utilization and TCOD, SCOD, and TOC at the high dosage levels.

The observations appear to contrast with the ANOVA for the ozone utilization data (Table 25), which indicated no significant effect of effluent quality on the amount of ozone utilized. However, the ANOVA averaged the data for both contactors over all dosage levels, while the regression analyses isolated and examined the effects of effluent quality at each individual dosage level for each contactor. These individual effects cancelled each other when averaged together in the ANOVA.

It is concluded that, at low doses (i.e., 4.9 and 9.7 mg/ℓ), ozone utilization was mass transfer limited, while at high dosages (i.e., >9.7 mg/ℓ) reaction kinetics influenced mass transfer. This contrasts with the

conclusions made for TCLR and FCLR. It means that, as ozone absorption by the effluent proceeded at low dosage levels, the ozone which had been transferred at those dosage levels was rapidly consumed in chemical reactions with oxidizable materials, the concentrations of which far exceeded the concentrations of microorganisms. Thus, coliform reduction at dosages >9.7 mg/ℓ was essentially reaction rate limited while utilization was mass transfer limited. At higher dosage levels, utilization exceeded that which would be predicted by Henry's Law, due to the effect of COD and TOC. However, the ozone which was transferred was immediately consumed by the organic demand causing the excessive absorption. Hence, at the high dosage levels, coliform reduction was again reaction rate limited, as was ozone utilization.

Ozone Utilization - Jet Scrubber--

Table 35 summarizes the correlation between ozone utilization in the jet scrubber and each effluent quality variable at different applied ozone dosage levels.

The correlation of ozone utilization with TCOD, SCOD, and TOC was significant at 4.7 and 13.1 mg/ℓ applied ozone, but not at 9.7 and 19.5 mg/ℓ. Perhaps more data points would have provided the necessary information to establish the correlation, since the r-values were near the critical value (i.e., 0.73) to be considered significant. The fact that the gas-liquid contact time in the jet scrubber was so low (3 sec at 75 ℓ/min liquid flow rate) may have been a significant factor affecting absorption in this contactor and/or reaction of ozone with organic matter.

Ozone Residual - Packed Column--

Table 36 summarizes the correlation between ozone residual in the packed column and each effluent quality variable at different applied ozone dosage levels.

It is clear from Table 36 that the magnitude of ozone residual in the effluent from the packed column was significantly affected by the presence of soluble organic material at all dosage levels studied. Thus, if the COD (total and soluble) or TOC was high, the ozone residual was low and vice versa. This would at least partially explain why coliform reduction in the packed column was significantly affected by replication, i.e., effluent quality (Tables 19 and 21).

Ozone Residual - Jet Scrubber--

Table 37 summarizes the correlation between ozone residual in the jet scrubber and each effluent quality variable at different applied ozone dosage levels.

It is evident from Table 37 that, as COD (total and soluble) and TOC increased, ozone residual in the effluent from the jet scrubber decreased at all dosage levels. Thus, the results from the jet scrubber are comparable to those from the packed column and the same conclusions apply.

TABLE 35. CORRELATION OF OZONE UTILIZATION IN THE JET SCRUBBER AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	Ozone Utilization Correlation Coefficients (r)* Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	0.91	0.63	0.96	0.62
SCOD	0.91	0.71	0.95	0.70
TOC	0.81	0.62	0.95	0.61
TSS	0.60	0.48	0.38	-0.08
TKN	-0.48	-0.87	-0.06	0.38
TURB	0.05	-0.12	0.31	0.66
NH_4-N	-0.69	-0.74	-0.79	-0.58
ORG-N	-0.12	-0.62	0.19	0.71

* 6 data points used to derive each r-value

TABLE 36. CORRELATION OF OZONE RESIDUAL IN THE PACKED COLUMN AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	Ozone Residual Correlation Coefficients (r)* Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	-0.96	-0.74	-0.97	-0.90
SCOD	-0.93	-0.77	-0.97	-0.86
TOC	-0.90	-0.71	-0.91	-0.96
TSS	-0.77	-0.21	-0.31	-0.78
TKN	0.48	0.64	0.04	0.58
TURB	-0.35	-0.37	-0.38	-0.09
ORG-N	0.08	0.29	-0.22	0.22

* 6 data points used to derive each r-value

TABLE 37. CORRELATION OF OZONE RESIDUAL IN THE JET SCRUBBER AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	Ozone Residual Correlation Coefficients (r)* Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	-0.88	-0.80	-0.96	-0.98
SCOD	-0.83	-0.85	-0.92	-0.90
TOC	-0.88	-0.76	-0.88	-0.94
TSS	-0.77	-0.30	-0.41	-0.56
TKN	0.34	0.78	0.14	0.35
TURB	-0.40	-0.04	-0.24	-0.02
NH_4-N	0.61	0.84	0.79	0.87
ORG-N	-0.01	0.46	-0.10	-0.01

* 6 data points used to derive each r-value

Ozone Consumption - Packed Column--

Table 38 summarizes the correlation between ozone consumption in the packed column and each effluent quality variable at different applied ozone dosage levels.

Data from Table 38 parallel the trends noted in the ozone utilization data (Table 34), namely, that at higher dosage levels, ozone consumption

TABLE 38. CORRELATION OF OZONE CONSUMPTION IN THE PACKED COLUMN AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	Ozone Consumption Correlation Coefficients (r)* Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	-0.34	0.23	0.76	0.98
SCOD	-0.37	0.21	0.73	0.87
TOC	0.06	0.40	0.85	0.86
TSS	0.07	0.61	0.39	0.38
TKN	0.27	-0.71	-0.24	-0.07
TURB	-0.68	-0.78	-0.29	0.16
NH_4-N	0.52	-0.03	-0.50	-0.81
ORG-N	-0.04	-0.82	-0.10	0.30

* 6 data points used to derive each r-value

increased as carbonaceous demand increased. Thus, at dosage levels greater than 9.7 mg/ℓ, the dosage was sufficiently high relative to COD and TOC that a change in COD or TOC caused a concomitant change in ozone consumption. At lower dosage levels, mass transfer was determined primarily by the concentration of ozone in the inlet gas and secondarily by organic demand.

Ozone Consumption - Jet Scrubber--

Table 39 summarizes the correlation between ozone consumption in the jet scrubber and each effluent quality variable at different applied ozone dosage levels.

A significant positive correlation is noted in Table 39 between ozone consumption and TCOD, SCOD, and TOC at all dosage levels. This contrasts with the data observed in the packed column in which positive correlations were observed only at dosage levels greater than 9.7 mg/ℓ.

Summary of Regression Analyses--

This section attempted to explain the variation observed in the microorganism reduction and ozone utilization data from the factorial experiments by quantitatively examining the effect of each effluent constituent on

TABLE 39. CORRELATION OF OZONE CONSUMPTION IN THE JET SCRUBBER AT DIFFERENT APPLIED OZONE DOSAGE LEVELS WITH EFFLUENT QUALITY PARAMETERS

Parameter	Ozone Consumption Correlation Coefficients (r)* Dose mg/ℓ			
	4.9	9.7	13.1	19.5
TCOD	0.90	0.74	0.96	0.76
SCOD	0.89	0.80	0.94	0.78
TOC	0.86	0.71	0.97	0.71
TSS	0.69	0.35	0.43	0.05
TKN	-0.45	-0.80	-0.16	0.27
TURB	0.02	-0.04	0.12	0.55
NH_3-N	-0.66	-0.79	-0.77	-0.67
ORG-N	-0.11	-0.52	0.06	0.63

* 6 data points used to derive each r-value

coliform reduction and ozone utilization, consumption, and residual at each dosage level studied. Results indicated that TCLR in the packed column was significantly and adversely affected by COD and TOC at ozone dosages less than 13.1 mg/ℓ, while at higher dosages demand exerted by nitrogenous materials became significant. In the jet scrubber, the same trends were noted

except that no correlations were found at 4.9 mg/ℓ ozone dose, where very little coliform reduction occurred anyway. Variations in the levels of nitrogenous materials did not significantly affect coliform reduction in the jet scrubber at any dosage level, presumably because of the exceedingly short reaction time available.

Ozone utilization and consumption in the packed column were significantly affected by COD and TOC at dosage levels greater than 9.7 mg/ℓ. At lower dosage levels absorption was governed primarily by Henry's Law. In the jet scrubber, ozone consumption and utilization were significantly affected by COD and TOC at essentially all dosage levels studied.

Ozone residual in both contactors was significantly affected by COD and TOC at all dosage levels.

PHASE 3 - CONTINUOUS OPERATION - PILOT PLANT EFFLUENT

During this phase of the investigation, an attempt was made to evaluate the reliability of each contactor in achieving a consistent 3-log reduction in coliform numbers, and to determine if the ozonation system (generator, drier, contactors, and analyzer equipment) could be operated for 100 continuous hours without major breakdowns. Ozone gas concentrations and flow rates were varied to maintain the highest possible ozone residuals in both contactors. This necessitated the use of high gas/liquid flow ratios in the jet scrubber, which in turn caused a reduction in percent ozone utilization. Ozone gas concentrations were monitored continuously by a Fisher and Porter Residual Ozone Analyzer. Grab samples of inlet and exhaust gas and ozonated effluent from each contactor were also taken manually for measurement. All bacteriological and physical-chemical analyses were performed on grab samples collected at 10-hour intervals. The experiment commenced at 7:00 AM on February 28, 1977, and terminated at 1:00 AM on March 3, 1977. The wastewater effluent was filtered prior to ozonation.

All systems operated satisfactorily for the entire 100 hours. Results are presented in Table 40. A 3-log reduction in total coliforms was achieved in 5 out of 10 samples in the packed column and only 1 out of 10 in the jet scrubber. A 3-log reduction in fecal coliforms was achieved in 4 out of 10 samples in the packed column and only 2 out of 10 in the jet scrubber. Thus, neither contactor gave reliable results in this particular wastewater. Short contact times (20 seconds in the packed column and 3 seconds in the jet scrubber) may partially explain the low microorganism reduction efficiencies observed. Wastewater quality may have played a key role in affecting the reliability of ozone disinfection in both contactors during these tests. The ranges of TCOD and TSS were 51 to 91 mg/ℓ (mean of 66 mg/ℓ) and 4 to 30 mg/ℓ (mean of 20 mg/ℓ), respectively. The TSS levels were considerably higher than in the prior testing period. Thus, it appears that additional wastewater treatment beyond secondary may be needed to achieve a reliable and consistent microorganism reduction by ozone, generated from air and applied in a packed column or a jet scrubber.

TABLE 40. CONTINUOUS OPERATION OF PACKED COLUMN AND JET SCRUBBER FOR THE 100-HOUR PERIOD OF FEBRUARY 28, 1977 TO MARCH 3, 1977

Date	Time	Contactor	G/L	Inlet ozone, mg/ℓ gas	Exhaust ozone, mg/ℓ gas	Ozone residual mg/ℓ liq.	TCLR	FCLR
2/28/77	0700	Packed column	1.2	13.4	5.7	0.7	3.22	2.69
		Jet scrubber	2.0	13.4	10.0	0.3	2.22	2.38
2/28/77	1700	Packed column	1.3	13.2	6.1	0.6	1.92	1.76
		Jet scrubber	2.0	13.2	10.0	0.3	1.08	1.62
3/01/77	0300	Packed column	0.9	14.7	3.9	0.2	1.42	1.46
		Jet scrubber	1.8	14.7	5.9	0.1	<1.00	<0.31
3/01/77	1300	Packed column	1.0	14.5	6.3	0.6	2.66	3.00
		Jet scrubber	2.0	14.5	11.2	0.3	2.52	3.17
3.01/77	2300	Packed column	0.6	17.0	5.5	0.5	3.00	2.23
		Jet scrubber	2.0	17.0	13.4	0.7	2.54	2.75
3/02/77	0900	Packed column	0.6	14.2	3.5	1.1	2.86	3.15
		Jet scrubber	2.0	14.2	12.7	1.0	2.28	3.00
3/02/77	1900	Packed column	1.2	14.3	6.4	0.4	2.85	2.71
		Jet scrubber	2.0	14.3	10.8	0.3	<1.16	1.50
3/03/77	0500	Packed column	1.0	11.9	2.4	0.5	3.04	3.42
		Jet scrubber	2.0	11.9	6.1	0.6	1.48	1.69
3/03/77	1500	Packed column	1.1	11.5	4.8	0.5	3.48	3.38
		Jet scrubber	2.0	11.5	9.2	0.4	1.18	1.50
3/04/77	0100	Packed column	1.8	10.9	6.4	1.0	3.38	2.50
		Jet scrubber	2.0	10.9	8.8	0.9	3.33	2.65

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APPENDIX A

THE MODIFIED KENNER-CLARK PROCEDURE FOR ENUMERATING SALMONELLA SPP.

The following describes the quantitative method used for enumerating Salmonella spp. from ozonated and unozonated activated sludge effluents. It is based on the original technique developed by Kenner and Clark (11) but with certain modifications.

SAMPLE TREATMENT

Concentration of organisms is attained by filtration through either membrane filters (0.45 µm) or glass fiber filters (Reeve Angel 984H ultra glass fiber filter). To obtain MPN results in the per 10 liter range, three 1000 ml samples are filtered through three membranes or glass fiber filters and the filters placed into enrichment tubes containing single strength enrichment broth (first row). Three 100 ml samples are filtered through three membrane or glass fiber filters and the filters placed into enrichment tubes containing single strength enrichment broth (second row). Three 10 ml samples are pipetted into three tubes with double strength enrichment broth (third row). row). Finally, three 1.0 ml samples are delivered into three tubes containing 9 ml of single strength enrichment broth (fourth row).

CONFIRMATION OF SALMONELLA SPP.

Primary enrichment medium is Dulcitol Selenite Enrichment (DSE) broth (Difco) and incubation is for 24 to 48 hours at 40 °C + 0.2 °C.

After incubation for 24 hours a loopful is removed from each culture tube, streaked onto Xylose Lysine Desoxycholate (SLD) agar (Difco) plates, and incubated at 35 °C for 24 hours. The DSE tubes are placed back into the 40 °C incubator, incubated for an additional 24 hours, and the isolation procedure on XLD plates is repeated as above. This allows an additional 24 hours of enrichment for any salmonellas which may have been originally present but had not yet grown to sufficient numbers to be detectable.

After the XLD plates have incubated 24 hours, they are examined for appearance of Salmonella-type colonies. Typical Salmonella colonies appear clear and pink-edges with black centers. The presumptive Salmonella colonies (at least 2 per plate and well isolated) are picked to Triple Sugar Iron Agar (TSIA) or Kligler's Iron Agar (KIA) slants (Difco) and Lysine Iron Agar (LIA) slants (Difco) for biochemical identification. Slants are incubated 24 hours

at 35 °C. If the black-centered colonies on the XLD plates are not well-isolated, another XLD plate must be streaked from the poorly isolated colony to purify the culture for subsequent biochemical identification. The typical reactions of Salmonella spp. on TSIA are alkaline slant, acid stab, and H_2S production. The reactions on LIA are alkaline slant and stab (i.e., positive for lysine decarboxylase) and H_2S production.

Confirmation is achieved in a very short time. The agglutination reaction, performed on the culture from the TSIA slant, using Salmonella O Antiserum Poly A-1, will confirm the presence of Salmonella spp. in a few minutes. Thus, the serological agglutination reaction will confirm or deny the presence of Salmonella.

If the TSIA and LIA reactions are not typical for Salmonella, repurification from the TSIA on XLD followed by picking subsequent black colonies (if any) back to TSIA and LIA is necessary before concluding that Salmonella are not present. This adds an additional two days of work to the test. Thus the time span for the entire method will produce results in as little as three to four days and as many as six days.

The method described is one of several methods in existence capable of quantifying Salmonella in natural samples. The limitations are indeed recognized. The precision of the 3-tube MPN is certainly inferior to the 5-tube procedure, but the trade-off in effort required in performing the 5-tube procedure for Salmonella enumeration does not justify its use at this time. It should be cautioned, however, that only an experienced microbiologist or microbiological technician should attempt the above procedure for routine analysis, as the number of tubes, plates, slants, etc., could overwhelm the investigator who has not been properly trained.

PACKED COLUMN MASS TRANSFER CALCULATIONS FOR PHASE I

DATE	G ℓ/min	Y_1 mg/l	Y_2 mg/l	$G(Y_1-Y_2)$ mg/min	Temp. °C	X_1 mg/l ww	HOT ℓww/ℓair	Y_1^* mg/l	$\ln \frac{Y_1-Y_1^*}{Y_2}$	ΔY_{LM} mg/l	KgVa ℓair/min
G = 37											
9-13	37	7.5	1.4	226	23	1.2	2.85	3.4	1.08	2.50	90
9-13	37	5.0	0.9	152	23	0.6	2.85	1.7	1.30	1.85	82
9-14	37	7.7	1.5	229	23.5	1.3	2.90	3.8	0.96	2.50	92
9-14	37	5.0	1.4	133	23.5	0.7	2.90	2.0	0.76	2.11	63
9-20	37	12.2	2.3	366	23	1.8	2.85	5.1	1.13	4.25	86
9-20	37	7.6	1.3	233	23	0.8	2.85	2.3	1.41	2.84	82
9-21	37	12.2	2.0	377	22	2.3	2.74	6.3	1.08	3.61	104
9-21	37	7.5	1.4	226	22	1.4	2.74	3.8	0.97	2.37	95
10-4	37	17.6	3.4	525	21	1.8	2.63	4.7	1.33	7.14	74
10-4	37	16.3	3.1	488	21	1.4	2.63	3.7	1.40	6.79	72
10-5	37	16.1	4.1	444	21	1.4	2.63	3.7	1.11	7.48	59
10-5	37	16.0	4.2	437	21	1.6	2.63	4.2	1.03	7.38	59
10-12	37	5.0	0.5	167	19	0.3	2.43	0.7	2.15	1.77	94
11-1	37	5.9	0.3	207	14.5	0.4	2.07	0.8	2.83	1.70	122
G = 73.6											
7-26	73.6	11.5	3.4	596	24	2.2	2.97	6.5	0.39	4.10	145
7-27	73.6	7.6	1.7	434	24	1.2	2.97	3.6	0.85	2.71	160
8-2	73.6	3.7	0.7	221	23	0.7	2.85	2.0	0.89	1.12	197
8-2	73.6	7.4	2.1	390	23	1.9	2.85	5.4	0.05	2.00	195
8-2	73.6	11.9	3.8	596	23	2.1	2.85	6.0	0.44	4.77	125
8-3	73.6	11.9	3.9	589	23	2.4	2.85	6.8	0.27	4.44	133
8-9	73.6	3.8	0.8	221	23	0.5	2.85	1.4	1.10	1.45	152
8-9	73.6	7.7	2.3	397	23	1.7	2.85	4.8	0.23	2.61	152
8-10	73.6	3.7	0.8	213	23	0.8	2.85	2.3	0.56	1.07	199
8-10	73.6	7.6	2.5	375	23	2.0	2.85	5.7	0.28	2.14	175
G = 110											
8-16	110	9.7	5.0	517	23	2.9	2.85	8.3	1.27	2.83	183
8-17	110	9.6	5.4	462	23	2.6	2.85	7.4	0.90	3.56	130
8-23	110	9.6	4.5	561	23	3.0	2.85	8.6	1.50	2.33	241
8-24	110	5.1	2.2	319	24	0.8	2.97	2.4	0.21	2.38	134
8-30	110	8.4	4.0	484	23	2.4	2.85	6.8	0.92	2.61	185
G = 147											
8-16	147	7.5	4.6	426	23	2.3	2.85	6.6	1.63	2.27	188
8-23	147	7.5	4.0	514	23	2.0	2.85	5.7	0.80	2.75	187
8-24	147	4.1	2.1	294	24	0.8	2.97	2.4	0.21	1.90	155
8-30	147	7.0	4.0	441	23	2.1	2.85	6.0	1.39	2.16	204
G = 55											
10-18	55	13.8	4.4	517	17	2.1	2.25	4.7	0.73	6.47	80
10-18	55	9.5	2.8	368	17	2.1	2.25	4.7	0.54	3.71	99
11-1	57	5.9	1.3	262	14.5	0.9	2.06	1.9	1.12	2.40	109

PACKED COLUMN MASS TRANSFER CALCULATIONS FOR PHASE 2

DATE	G ℓ/min	Y_1 mg/l	Y_2 mg/l	$G(Y_1-Y_2)$ mg/min	Temp. °C	H@T ℓww/ℓair	X_1 mg/l ww	Y_1^* mg/l	ℓn $\frac{Y_1-Y_1^*}{Y_2}$	ΔY_{LM} mg/l	KgVa ℓair/min
G = 37											
1-27-77	37	9.7	3.2	240	14	2.04	0.1	0.2	1.09	5.78	42
1-31-77	37	9.6	2.1	278	14	2.04	0.6	1.2	1.39	4.53	61
2-7-77	37	9.6	2.6	259	13	2.00	0.2	0.4	1.26	5.24	49
2-8-77	37	9.6	3.7	218	14	2.04	<0.1	0.2	0.93	6.13	36
2-8-77	37	9.5	3.0	240	14	2.04	<0.1	0.2	1.13	5.58	43
1-24-77	37	9.9	2.2	285	13	2.00	0.9	1.8	1.30	4.54	63
G = 76											
1-27-77	76	9.7	4.9	365	14	2.04	0.3	0.6	0.62	6.78	54
1-31-77	76	9.7	4.7	380	14	2.04	1.4	2.9	0.37	5.69	67
2-7-77	76	9.8	4.3	418	13	2.00	0.4	0.8	0.74	6.36	66
2-8-77	76	9.6	4.0	426	14	2.04	0.2	0.4	0.83	6.24	68
2-8-77	76	9.7	3.6	464	14	2.04	0.1	0.2	0.97	6.08	76
1-24-77	76	9.6	4.1	418	13	2.00	0.9	1.8	0.64	5.75	73
G = 101											
1-27-77	101	9.8	5.0	485	14	2.04	0.4	0.8	0.59	6.81	71
1-31-77	101	9.7	5.2	455	14	2.04	1.6	3.3	0.21	5.78	79
2-7-77	101	9.9	5.6	434	13	2.00	1.1	2.2	0.32	6.52	67
2-8-77	101	9.9	5.0	495	14	2.04	0.4	0.8	0.60	6.85	72
2-8-77	101	9.8	4.6	525	14	2.04	0.2	0.4	0.71	6.72	78
1-24-77	101	9.9	5.7	428	13	2.00	1.7	3.4	0.13	6.10	70
G = 151											
1-27-77	151	9.8	5.8	604	14	2.04	0.9	1.8	0.32	6.84	88
1-31-77	151	9.7	5.8	589	14	2.04	1.6	3.3	0.10	6.10	97
2-7-77	151	9.9	6.4	528	13	2.00	0.9	1.8	0.23	7.22	73
2-8-77	151	9.8	5.6	634	14	2.04	0.2	0.4	0.52	7.34	86
2-8-77	151	9.8	5.6	634	14	2.04	0.4	0.8	0.47	7.17	88
1-24-77	151	9.7	6.4	498	13	2.00	1.9	3.8	0.08	6.17	81

JET SCRUBBER MASS TRANSFER CALCULATIONS FOR PHASE I

DATE	G ℓ/min	ΔY_1 mg/ℓ	Y_2 mg/ℓ	$G(Y_1-Y_2)$ mg/min	Temp. °C	X_2 mg/ℓ	HOT ℓww/ℓair	Y_2^* mg/ℓ	$\ell n \frac{Y_2-Y_2^*}{Y_1}$	ΔY_{LM} mg/ℓ	KgVa ℓair/min
G = 37											
9-13	37	7.6	3.9	137	23	0.5	2.85	1.4	1.11	4.59	30
9-13	37	5.3	2.1	118	23	0.2	2.85	0.6	1.26	3.02	39
9-14	37	7.7	3.8	144	23.5	0.4	2.90	1.2	1.09	4.68	31
9-14	37	5.3	2.4	107	23.5	<0.1	2.90	0.3	0.96	3.33	32
9-20	37	12.0	4.5	278	23	0.5	2.85	1.4	1.35	6.59	42
9-20	37	7.4	4.0	126	23	0.2	2.85	0.6	0.78	5.13	25
9-21	37	12.0	5.0	259	22	0.6	2.74	1.6	1.26	6.83	38
9-21	37	7.7	4.5	118	22	0.3	2.74	0.8	0.73	5.48	22
10-4	37	17.4	8.1	344	21	1.2	2.62	3.1	1.25	9.92	35
10-4	37	16.1	8.3	289	21	0.6	2.62	1.6	0.88	10.68	27
10-5	37	16.2	8.6	281	21	1.0	2.62	2.6	0.99	10.30	27
11-1	37	5.9	2.9	111	14.5	0.3	2.06	0.6	0.94	3.82	29
11-2	32	9.2	4.5	150	16	0.5	2.18	1.1	1.00	5.83	26
G = 55											
10-18	55	13.8	7.1	369	17	2.7	2.25	6.1	2.62	4.89	75
10-18	55	9.5	6.8	149	17	1.3	2.25	2.9	0.89	6.29	24
11-1	57	5.9	3.5	137	14.5	0.3	2.06	0.6	0.71	4.22	32
G = 73.6											
7-26	73.6	11.5	7.2	316	24	0.9	2.97	2.7	0.94	7.46	42
7-27	73.6	7.5	3.9	265	24	0.5	2.97	1.5	1.14	4.48	59
8-2	73.6	3.7	1.7	147	23	0.0	2.85	0.0	0.78	2.57	57
8-2	73.6	7.3	3.3	294	23	0.3	2.85	0.9	1.11	4.40	67
8-2	73.6	12.0	6.5	405	23	0.7	2.85	2.0	0.98	7.65	53
8-3	73.6	12.0	6.6	397	23	0.7	2.85	2.0	0.96	7.71	51
8-9	73.6	3.7	1.8	140	23	0.2	2.85	0.6	0.90	2.81	50
8-10	73.6	7.9	4.7	236	23	0.7	2.85	2.0	1.07	4.84	49
G = 110											
8-16	110	9.6	7.5	231	23	1.6	2.85	4.6	1.20	5.60	41
8-17	110	9.8	6.2	396	23	0.9	2.85	2.6	1.00	6.19	64
8-23	110	9.8	6.8	330	23	1.5	2.85	4.3	1.37	5.34	62
8-24	110	5.3	3.4	209	24	0.7	2.97	2.1	1.41	2.85	73
8-30	110	8.5	7.0	165	23	1.1	2.85	3.1	0.78	5.90	28
G = 147											
8-16	147	7.4	5.7	250	23	1.2	2.85	3.4	1.17	4.36	57
8-17	147	7.4	5.8	235	23	0.7	2.85	2.0	0.67	5.40	44
8-23	147	7.7	5.6	309	23	0.6	2.85	1.7	0.68	5.59	55
8-24	147	4.0	2.6	206	24	0.4	2.97	1.2	1.05	2.48	83
8-30	147	6.9	5.4	220	23	0.7	2.85	2.0	0.71	4.95	44

JET SCRUBBER MASS TRANSFER CALCULATIONS FOR PHASE 2

DATE	G ℓ/min	Y_1 mg/l	Y_2 mg/l	$G(Y_1-Y_2)$ mg/min	Temp. °C	X_2 mg/l ww	HOT ℓww/ℓair	Y_2^* mg/l	$\frac{\ln Y_2 \cdot Y_2^*}{Y_1}$	ΔY_{LM} mg/l	KgVa ℓair/min
G = 37											
1-27-77	37	9.7	4.2	204	14	<0.1	2.04	0.2	0.85	6.67	31
1-31-77	37	9.6	4.6	185	14	0.1	2.04	0.2	0.78	6.67	28
2-7-77	37	9.6	4.5	189	13	<0.1	2.00	0.2	0.80	6.60	29
2-8-77	37	9.6	3.7	218	14	<0.1	2.04	0.2	1.01	6.05	36
2-8-77	37	9.5	3.3	229	14	<0.1	2.04	0.2	1.12	5 71	40
1-24-77	37	9.9	5.4	166	13	0.2	2.00	0.4	.68	7.17	23
G = 76											
1-27-77	76	9.7	6.6	236	14	0.2	2.04	0.4	0.45	7.82	30
1-31-77	76	9.7	7.2	190	14	0.4	2.04	0.8	0.42	7.94	24
2-7-77	76	9.8	6.5	251	13	0.2	2.00	0.4	0.47	7.80	32
2-8-77	76	9.6	5.7	296	14	<0.1	2.04	0.2	0.56	7.36	40
2-8-77	76	9.7	5.5	319	14	<0.1	2.04	0.2	0.60	7.28	44
1-24-77	76	9.6	6.5	236	13	0.3	2.00	0.6	0.49	7.60	31
G = 101											
1-27-77	101	9.8	6.7	313	14	0.2	2.04	0.4	0.44	7.92	40
1-31-77	101	9.7	7.3	242	14	0.5	2.04	1.0	0.43	7.88	31
2-7-77	101	9.9	7.2	273	13	0.3	2.00	0.6	0.41	8.14	34
2-8-77	101	9.9	6.7	323	14	<0.1	2.04	0.2	0.42	8.08	40
2-8-77	101	9.8	6.4	343	14	0.1	2.04	0.2	0.46	7.86	44
1-24-77	101	9.9	7.6	232	13	0.8	2.00	1.6	0.50	7.80	30
G = 151											
1-27-77	151	9.8	6.2	544	14	0.2	2.04	0.4	0.52	7.63	71
1-31-77	151	9.7	7.3	362	14	0.4	2.04	0.8	0.40	7.99	45
2-7-77	151	9.9	7.8	317	13	0.4	2.00	0.8	0.35	8.37	38
2-8-77	151	9.8	7.2	393	14	<0.1	2.04	0.2	0.34	8.32	47
2-8-77	151	9.8	7.2	393	14	<0.1	2.04	0.2	0.34	8.32	47
1-24-77	151	9.7	7.8	287	13	0.7	2.00	1.4	0.42	7.93	36

APPENDIX C

SAFETY PRECAUTIONS USED IN THE OZONE TEST FACILITY

A safety program was instituted for this research project based on the draft report of "Technical Standards for Ozone" by the Occupational Safety and Health Administration (OSHA). The major thrust of the program was to provide containment and destruction of residual ozone in and near the working environment.

The maximum permissable exposure concentration of ozone in air is less than 0.1 part per million (ppm) on a volumetric basis. The action level is 0.05 ppm ozone. This low level of exposure was never exceeded during the evaluation of the contactors.

Four major areas of control in the research facility were established to guard against the accidental release of ozone into the work area.

POTENTIALLY HIGH OZONE CONCENTRATION AREA

The area between the generator and contactors was the most vulnerable area to accidental ozone release because of the location of transmission lines containing the highest levels of ozone in the facility (approximately 2,000 to 15,000 ppm). The transmission lines were fabricated from aluminum tubing and located underneath or alongside support beams to protect the lines from accidental falling objects.

If an accidental ozone release had occurred, the operators were instructed to immediately vacate the area. An electrical cut-off switch was located in an adjacent room for de-energizing the ozonator. A self-contained breathing apparatus with a full facepiece and operated in a pressure demand mode was located at an exit door from the building. During an emergency, re-entry would be permissable with this apparatus into an area containing toxic levels of ozone.

POTENTIALLY MODERATE OZONE CONCENTRATION AREA

The exhaust gases from the contactors contained ozone at concentrations between 300 and 5000 ppm. In this area, PVC pipe was used to convey the ozone from the contactors to a thermal decomposer. The decomposer was controlled to maintain a temperature of 290 ^{o}C to insure complete decomposition of the ozone before discharge to the outside atmosphere. A test was conducted on the effect of temperature on ozone decomposition. Results showed that temperatures above 260 ^{o}C were required to achieve a 90+% destruction of ozone. The data from this test are shown in Table C-1.

TABLE C-1. EFFECT OF TEMPERATURE ON OZONE GAS DECOMPOSITION

Temp. °C	Ozone conc., mg/ℓ In	Out	Ozone decomposed %
90	7.0	6.8	2
150	7.0	2.3	67
200	7.0	0.8	86
260	5.2	0.1	98

A sample outlet was located in the line from the decomposer to the outside vent. During normal operation gas samples from the decomposer were checked by a Dasibi analyzer. No evidence of ozone in the gas released to the outside atmosphere was even indicated.

POTENTIALLY LOW OZONE CONCENTRATION AREA

After ozone treatment, the secondary effluent was discharged into an open trench. Residual ozone flashed (vaporized) from solution and ozone could be detected in the work area. To remedy the situation, a hood and exhaust system were installed at the trench to collect the ozone gas and vent it outside the building. Following completion of the jet scrubber evaluation, the scrubber was modified by installing a recirculating sodium thiosulfate solution through the jet scrubber to neutralize the ozone escaping from the discharging effluent. Ozone from the effluent was collected by a fan and duct system and vented to the jet scrubber.

SAMPLING STATION

A central gas sampling station containing gas outlets from all gas transmission lines was located on a laboratory bench adjacent to the ozone contactors. During wet gas analyses, the gas outlets required purging to insure collection of a representative sample. These ozone enriched gases were decomposed by bubbling the purge gas through a concentrated solution of potassium iodide. This technique was effective for maintaining an ozone free work area.

A Dasibi analyzer was located at the central sampling station for continuous monitoring of various ozone gas streams. The exit gas from the Dasibi analyzer was vented into a line leading to the exhaust system located at the effluent discharge trench.

In addition to the above preventive measures, all systems were tested with air for leakage. Joints were bubble checked with soap solution before ozone was introduced into the system.